PNWD-3817

# Riparian Buffer Zones in the Interior Columbia River Basin: A Review of Best Available Science

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**March 2008**

**Prepared for**
**National Oceanic & Atmospheric Administration**
**National Marine Fisheries Service**
**Northwest Fisheries Science Center**
**Seattle, Washington**

**Battelle Memorial Institute**
**Pacific Northwest Division**

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# Executive Summary

The riparian corridors of the interior Columbia River Basin, like those found in other regions of the country, generally comprise only a small portion of the total watershed area, yet provide disproportionately important ecosystem functions. Riparian zones of the interior Columbia River Basin encompass a diversity of aquatic ecosystems from arid lowlands to mountain foothills. These riparian areas can span gradients in elevation, temperature, and precipitation. The climatic and geophysical differences result in a gradient in riparian plant communities. Natural, unimpacted riparian zones typically support a full suite of riparian functions. These include temperature regulation (e.g., shading), sediment filtration, nutrient processing, streambank stabilization, and enhanced habitat features, as well as pollutant filtration and capture.

This report summarizes the current best available science on the effectiveness of riparian buffers in agricultural areas applicable to the interior Columbia River Basin. This synthesis provides guidance for evaluating the effectiveness of voluntary riparian conservation efforts on agricultural lands specific to the study region. A discussion of the Conservation Reserve Enhancement Program is also included.

Few studies have specifically focused on the effectiveness of riparian buffers in agricultural areas in the interior Columbia River Basin. For the most part, existing studies focus on the water-quality benefits of buffers in agricultural settings. Few studies address the habitat functions or other ecological benefits of riparian buffers. However, despite the lack of research specific to the study area, there is a significant body of scientific literature from throughout the world that addresses the utility of using riparian management zones and buffers to protect receiving waters in areas dominated by agricultural land-use activities. This report summarizes the findings of applicable studies that qualify as best available science. Based on the body of research, it is evident that riparian buffers, when properly designed and maintained, can significantly reduce the impacts of agricultural land-use activities on streams, lakes, and wetlands.

The efficacy of pollutant filtration within agro-riparian studies has been derived under experimentally manipulated conditions as well as in situ-based studies. Compared with single species buffers (e.g., grass and forest), stream-side vegetation comprised of multiple vegetation types (e.g., a combination of grasses, shrubs, and trees) has been found to increase the efficacy of pollutant filtration in agricultural landscapes. Compared with empirically derived agro-riparian studies, the minimum buffer width (e.g. 35 feet) required by Washington CREP likely provides protection to streamside ecosystems through sediment, nutrient, and pesticide filtration. Based on the findings of this literature review, buffer widths within agricultural landscapes have not been empirically evaluated with regard to providing fish and wildlife habitat, LWD inputs, and temperature regulation to nearby streams. Using data from forested riparian studies as a template for agro-riparian ecosystems indicates a 35 foot buffer may not be effective in supporting all streamside ecosystem processes.

# Acknowledgments

This review was made possible through support from the NOAA NW Fisheries Science Center, specifically Dr. Michael Pollock and Dr. Tim Beechie.

# Acronyms

| | |
|---|---|
| BAS | best available science |
| BMP | best management practice |
| CPOM | coarse particulate organic matter |
| CREP | Conservation Reserve Enhancement Program |
| DO | dissolved oxygen |
| ESC | erosion and sediment control |
| FPOM | fine particulate organic matter |
| FSA | Farm Service Agency |
| LWD | large woody debris |
| N | nitrogen |
| NOAA | National Oceanic & Atmospheric Administration |
| NRCS | Natural Resources Conservation Service |
| NWFSC | Northwest Fisheries Science Center |
| OM | organic matter |
| P | phosphorous |
| REMM | riparian ecosystem management model |
| RiMS | riparian management system model |
| RMZ | riparian management zone |
| TSS | total suspended solids |
| USDA | U.S. Department of Agriculture |
| USGS | U.S. Geological Survey |
| VFS | vegetated filter-strip |

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# 1.0 Introduction

The objective of this report is to summarize the current best available science (BAS) on the effectiveness of riparian buffers in agricultural areas of the interior Columbia River Basin. The Northwest Fisheries Science Center (NWFSC), of National Oceanic & Atmospheric Administration (NOAA) Fisheries, Department of Commerce, is the government agency charged with the mission of stewardship for living marine resources. The purpose of this synthesis is to guide NOAA-NWFSC staff in evaluating the effectiveness of voluntary riparian conservation efforts on agricultural lands, specific to the interior Columbia River basin. Currently, NOAA has no comprehensive summary of buffer effectiveness in non-forest lands, which makes evaluation of the salmon recovery potential of small, intensively managed riparian buffers in areas dominated by agricultural land-use activities problematic. A comprehensive analysis of buffer management scenarios will facilitate the evaluation of the adequacy of conservation and restoration project proposals. Such a reference is intended to help streamline the review process and economize staff time at NOAA-NWFSC.

We worked closely with NWFSC scientists to review the effectiveness of agricultural buffers (various widths and vegetation types) for conservation of ecological functions in streams (shading, sediment filtration, nutrient filtration, and pesticide filtration). Our review focused on documenting levels of ecosystem function that can be achieved using buffers typical of the Conservation Reserve Enhancement Program (CREP).

Our report summarizes the effectiveness of agricultural buffers for conservation of ecological functions in streams in the interior Columbia basin, and includes a review of the following buffer conditions and functional response variables:

*Buffer Conditions*

- Buffer Type (grass, shrubs, trees, etc.)
- Buffer Width (to include "no buffer" and "natural" as end members)
- Stream Type (incised channels and non-incised channels)
- Soil attributes (i.e., porosity and clay content)

*Response V*ariables

- Sediment Filtration
- Nutrient Filtration
- Pollutant (e.g., insecticide and herbicide) Filtration
- Temperature (shade) Regulation

# 2.0 Background

Riparian zones are defined as transitional areas between terrestrial and aquatic ecosystems and are distinguished by gradients in biophysical conditions, ecological processes, and biota. Climate has a strong regional influence on the structure and function of riparian areas. Riparian zones are areas through which surface and subsurface hydrology connect aquatic ecosystems with adjacent uplands. Riparian areas include those portions of terrestrial ecosystems that significantly influence exchanges of energy and matter with aquatic ecosystems (i.e., zones of influence). Riparian areas are located adjacent to perennial, intermittent, and ephemeral streams, lakes, and estuarine-nearshore marine shorelines (NRC 2002). An important feature of this definition is the concept of riparian zones having gradients in ecological structure and function between upland terrestrial environments and associated aquatic ecosystems (Figure 1).

Riparian "ecotones" cannot be thought of in isolation from their associated aquatic or upland ecosystems. They are intrinsically linked to the processes and functions of those ecosystems. Riparian areas perform important hydrologic, chemical, geomorphic, and biological functions, which generally fall into three major categories: 1) hydrologic and sediment transport dynamics, 2) biogeochemical (organic matter and nutrient) cycling, and 3) habitat and food-web maintenance (NRC 2002). Riparian zones are also critical in maintaining the biodiversity of both aquatic and terrestrial (upland) ecosystems. Riparian zones, in proportion to the overall area within a watershed, tend to perform more biologically productive functions than do the surrounding upland areas (NRC 2002).

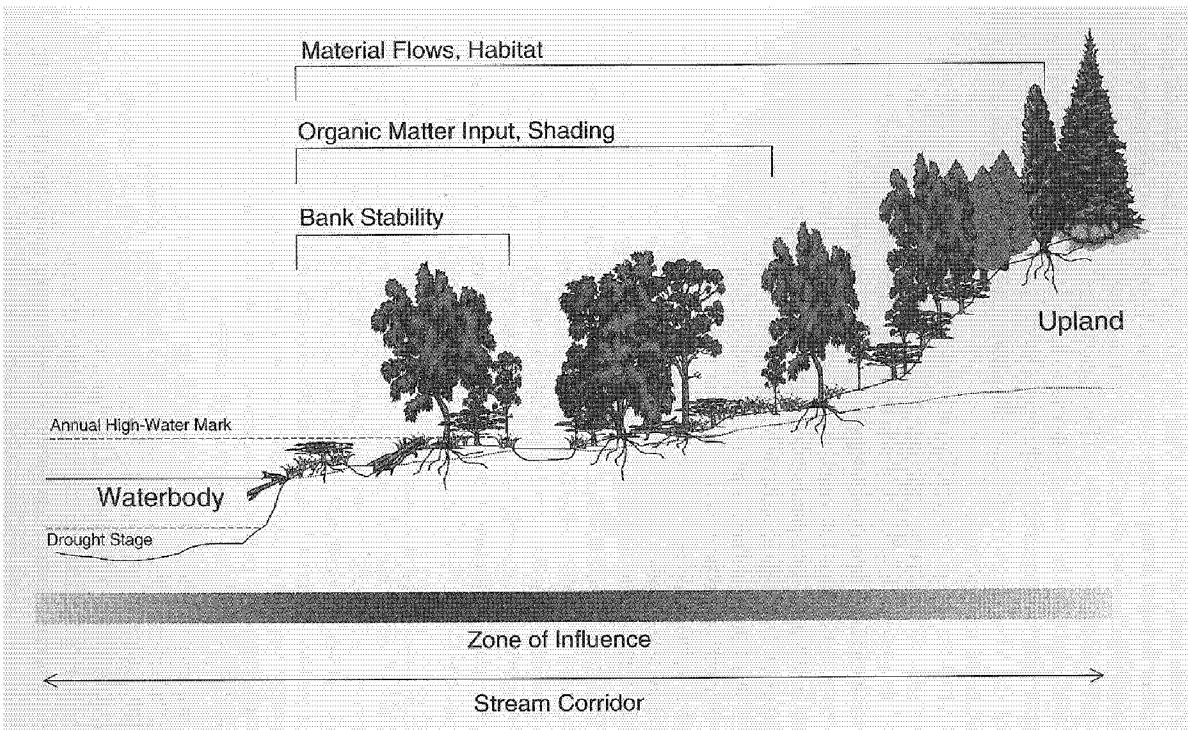


**Figure 1.** Riparian zone of influence showing gradients of ecological structure and function between upland and aquatic ecosystems (NRC 2002).

Native vegetation, in general, plays a critical role in healthy watersheds, whereas riparian vegetation is even more tightly coupled to the health of aquatic ecosystems (Naiman et al. 2000). Plant communities are dynamic. Soils, nutrients, and woody debris move from one area to another through precipitation and erosion, leaching, wind, natural and human disturbances, and a variety of other mechanisms. Plant communities in riparian areas help determine what, how much, and when materials from upland areas enter the stream ecosystem. For example, a wide, mature riparian forest will capture large quantities of soil and sediment, nutrients, and woody debris, adding richness and complexity to soil and plant communities near the water and protecting water from excessive nutrient or soil inputs (Figure 2). A fine balance exists between having enough and having too much of these inputs to the stream. Riparian areas, and consequently the structure, functions, and processes occurring within and around the stream, are fundamentally altered when upland and riparian vegetation is removed (Naiman et al. 2000).

Vegetative communities in the riparian zone continuously change, reflecting a dynamic landscape. Heterogeneity in landform, microclimate gradient, site productivity, and disturbance regime all play important roles in influencing forest structure, species richness, and colonization by exotic plants (Naiman et al. 2000). Riparian vegetation refers specifically to plant communities occurring within the riparian area that are adapted to wet conditions and are distinct from upland communities (Gregory et al. 1991). Riparian areas typically comprise herbs and grasses, shrubs, deciduous trees, and coniferous stands of various ages. Younger vegetation usually occurs immediately adjacent to the stream channel and in floodplain areas. This community commonly consists of deciduous trees, shrubs, and groundcover. Generally, older plant communities exist farther from the channel and are typically dominated by trees (Gregory et al. 1991, Naiman & Decamps 1997, Naiman et al. 2000).

The distribution, structure, and composition of riparian plant communities are largely determined by climate, light and water availability, topographic features, chemical and physical properties of the soil (including moisture and nutrient content), the existence of tributary and groundwater flows, and natural disturbance regimes.

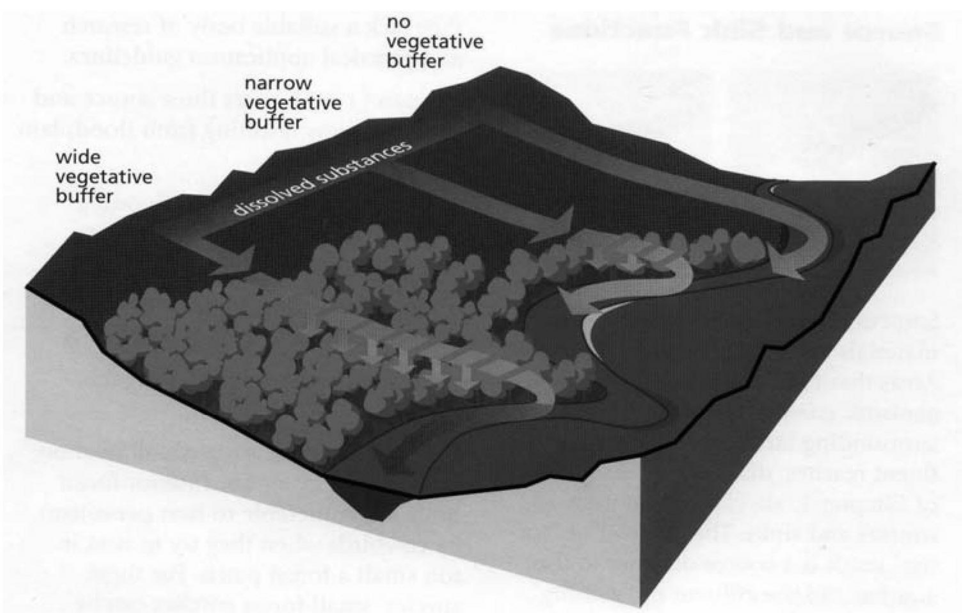


**Figure 2**. Functional extent of riparian buffer vegetation (FISRWG 1998).

Aquatic and terrestrial ecosystem integrity is greatly influenced by the quantity, composition, and structure of riparian plant communities. Plant communities that cover large areas and have an array of vertical (e.g., trees versus shrubs) and horizontal (e.g., young stands versus old growth) structural characteristics can support numerous animal species. In addition, riparian vegetation, through its root system and input of woody debris, influences stream channel characteristics. Riparian vegetation also directly affects aquatic organisms by providing organic materials to the aquatic food web (Gregory et al. 1991).

Riparian areas have adapted to the natural hydrologic disturbance regimes of their region. Historical and current land-use activities have imposed significant negative impacts on riparian areas throughout the country (NRC 2002). Effects include hydrologic alterations (e.g., dams and water withdrawal) and geomorphic modifications (e.g., channelization and filling) of aquatic ecosystems. Human encroachment into riparian zones, as well as the alteration or removal of native riparian vegetation, has significantly degraded riparian areas throughout the country (NRC 2002). In addition, riparian areas are not immune to land-use and mismanagement activities in associated uplands, which can result in detrimental impacts to stream-riparian ecosystems (Naiman et al. 2000).

A wide range of human land-use activities can adversely affect riparian habitats, including urban development and agriculture. Agricultural practices, such as land clearing, grazing, and crop production, can influence the integrity of riparian systems through direct and indirect mechanisms, including water withdrawal, disruption of biogeochemical processes, and chronic exposure to pollutants in agricultural runoff (NRC 2002). The most common impact on riparian zones in areas dominated by agricultural land-use activities includes the removal of native vegetation and the conversion of natural ecosystems to row-crop agriculture or grazing areas. Stream channelization and streambank armoring are also common forms of degradation of stream-riparian ecosystems in agricultural regions. Fragmentation of stream corridors by roads, utility crossings, and other forms of development has also had a significant impact on riparian areas (NRC 2002).

# 3.0 Interior Columbia River Basin Riparian Zones

The riparian ecotones of the interior Columbia River Basin, like those found in other regions of the country, generally comprise only a small portion of the total watershed area, yet provide disproportionately important ecosystem functions (Wissmar 2004). Riparian zones in the interior Columbia River region encompass aquatic ecosystems from arid lowlands to mountain foothills (Figure **3**). These riparian areas span gradients in elevation, temperature, and precipitation. The climatic and environmental differences result in a gradient in riparian plant communities (Kovalchik & Clausnitzer 2004)

Quigley et al. (1997a) conducted an ecosystem assessment of discrete geoclimatic subregions in the Columbia Plateau, which includes the central and southern regions of eastern Washington and portions of eastern Oregon. The differences in elevation, temperature, soil structure, and hydrology within each of these subregions strongly influence riparian ecosystem functions and processes.


Figure 3a. Touchet River Valley, Walla Walla County.


Figure 3b. Riparian gallery forest, Touchet River, Walla Walla County.


Figure 3c. Gravel storage within riparian zone. Touchet River, Walla Walla County.


Figure 3d. Riparian forest, upper Touchet River, Walla Walla County.


Figure 3e. Agricultural activities within the Touches River Valley. Walla Walla County.


Figure 3f. Multi-species riparian zone. Touchet River, Walla Walla County.

**Figure 3.** Riparian zones within the interior Columbia River Basin host a gradient in flora and fauna communities, provide numerous ecosystem functions, and are affected by a variety of human activities.

The Columbia Plateau subregions include the following (Quigley et al. 1997a):

- Foothills composed mainly of loess over basalt that has been modified by fluvial and Aeolian processes
- Plateaus and high plains of fluvial and lacustrine sediment and ash deposits created by Aeolian, fluvial, and lacustrine processes
- Intermountain basins and valleys of valley fill, alluvium, and lacustrine materials overlying volcanic and sedimentary rocks
- Glaciated mountains of volcanic and sedimentary rocks that have been modified by colluvial, fluvial, residual, and glacial processes
- Plateaus and foothills composed mainly of tuffs and basalts that have been modified by fluvial and Aeolian processes.

In general, riparian vegetation in the interior Columbia River basin can be divided into two main community types. At higher elevations, the riparian zone is dominated by several species of trees, mostly conifers (Kovalchik & Clausnitzer 2004). In the lower elevation areas where agricultural activity is concentrated, the climate is more arid, and the plant community is dominated by shrubs, sedges, rushes, forbs, and grasses, with some species of trees also present (Crawford 2003). Appendix A contains a list of native riparian plant species common to the interior Columbia River basin. The gradient division of riparian characteristics and community types observed in eastern Washington is also apparent in eastern Oregon. A mixture of grasses, shrubs, and trees composes the vegetation among the arid lowlands, whereas the higher elevations of this region are dominated by pine and fir forests (Li et al. 1994).

The riparian zones of the interior Columbia River basin of eastern Washington and Oregon perform the same array of functions as riparian areas found in other regions (Wissmar 2004). Riparian corridors in mountain or foothill areas of the region are often dominated by trees, including conifers (hemlock, fir, cedar, and spruce) and deciduous species (willow, aspen, cottonwood, alder, and maple). In these areas, the riparian zone provides shade and temperature regulation, as well as organic matter (OM) and large woody debris (LWD) recruitment (Herrera 2004). These riparian zones also filter nutrients, sediment, and pollutants to maintain stream water quality. Providing habitat for fish and wildlife is also an important riparian function (Kovalchik 1992).

In lower elevation, semiarid subregions, the riparian plant community tends to be characterized by a mixture of deciduous trees, shrubs, sedges, rushes, and grasses (Appendix A), depending on the hydro-geomorphic and soil characteristics of the location (Crawford 2003). Whereas shade and temperature regulation is still an important function, LWD recruitment is less important. However, streambank stabilization can be an even more important function of riparian vegetation in arid or semiarid stream corridors. Lowland riparian zones also filter nutrients, sediment, and pollutants to maintain stream water quality. Providing habitat is also an important riparian function in lowland riparian corridors. Riparian areas containing high water tables can act as hydrologic reservoirs that help maintain stream flows during the dry season (Wissmar 2004).

As is the case in other regions, land-use activities in the interior Columbia River basin have resulted in a significant degradation in overall riparian quality (Wissmar 2004). Agricultural activity has been especially hard on riparian ecotones. In many areas affected by agricultural activity, incised channels with highly altered riparian vegetation communities are common (Beschta 1997). Stream channelization has also resulted in markedly simplified stream systems that are much different from complex and diverse native stream ecosystems.

The cumulative impacts of human land-use activities, including agriculture and livestock grazing, have also significantly altered the sediment regime of most watersheds in the region. Agricultural runoff often contains a greater load of fine sediment. This fine sediment and OM can also carry excess nutrients from crop fertilizers or livestock manure, as well as pollutants such as pesticides and herbicides (Wissmar 2004).

Agricultural activity also tends to have a negative effect on the natural hydrologic regime. As the hydrologic regime between subsurface flow and the streambed are disconnected, riparian structure can revert from communities dominated by sedge, willow, and cottonwood to vegetation tolerant of xeric habitats: sagebrush, cheatgrass, and juniper (Beschta 1997). The vegetative communities and biotic constituents of arid and semiarid lands such as those encountered in eastern Washington and Oregon are often particularly sensitive to human-induced ecosystem disturbance (Wissmar 2004).

# 4.0 Riparian Buffers

The term "riparian buffer" is often used in a general sense to describe the vegetated area alongside a river, stream, lake, wetland, or nearshore estuarine area. The term "buffer" is typically used in a management context and should only be used to denote an area set aside and managed to protect a natural area from the effects of surrounding land-use or human activities.

Buffers can be forested areas, landscaped areas, or even grassy swales or "vegetated filter-strips" (VFSs) designed for water-quality treatment. In this respect, buffers are often designed to perform a specific function or set of functions, such as filtering pollutants or providing shade for a water body. For example, a VFS composed of grass can be designed to filter pollutants from stormwater or agricultural runoff prior to this water emptying into a nearby wetland, stream, or river.

It is a generally accepted principle that riparian buffers should be designed based on the resource to be protected and in proportion to the potential threat of the surrounding human land-use activities. Based on this concept, the more sensitive or valuable the natural resource, the greater the need for a more protective buffer. By the same token, the more intense the surrounding land-use or the more potential for damage to the resource, the more protection the buffer should provide.

Buffers should not be confused with the natural riparian zone, which is an integral part of the natural ecosystem. The term "riparian management zone" (RMZ) is often used to describe the combination of the stream-riparian ecosystem and the buffer zone.

In general, the effectiveness of riparian buffers is dependent on inherent buffer characteristics, including buffer extent (e.g., width), buffer quality (e.g., vegetative composition and maturity), and longitudinal continuity (e.g., level of fragmentation). External factors operating at multiple scales can also influence the effectiveness of agricultural buffers:

- runoff volume and velocity
- slope or gradient
- contributing flow length
- flow-path surface characteristics
- water-table and groundwater characteristics
- soil composition and condition.

In agricultural areas, buffers are typically designed to provide streambank stabilization and reduce fine sediment production from streambank erosion. Riparian buffers also connect streams with groundwater in agricultural areas. In addition, agricultural buffers can be designed to retain or filter sediment, as well as nutrients and pollutants in agricultural runoff (NRC 2002).

Agricultural buffers can also be designed to provide habitat for terrestrial and aquatic biota. The dynamic structure in fish communities inherently oscillates over different time scales; however, when studied over long periods, the connectivity of riparian corridors has been found to buffer the impact of agricultural land use to fish communities (Wichert & Rapport 1998). Furthermore, the type of agricultural practices influence riparian health and fish communities. Improvement to riparian ecosystems was noted when agriculture shifted from grazing to small-scale tillage operations (Wichert & Rapport 1998).

In agricultural regions across the country, different management principles have resulted in non-uniform riparian buffer design standards (Schultz et al. 2004). A three-zone approach is often implemented as a means for creating a self-sustainable riparian ecosystem with the ability to intercept pollutants from agricultural areas (USDA 2000) (Figure 4). The zone nearest the field edge supports grasses and acts as a filter for sediment, nutrients and pesticides. The middle zone consists of a managed forest where pollutants are further filtered by herbaceous and woody vegetation. Pollutants not initially filtered or retained by the grass strip are filtered by the second zone (Lowrance 1997). The zone closest to the stream is intended to provide habitat-related functions and processes, including shade and microclimate, as well as LWD recruitment and OM inputs to support the food web of aquatic biota (USDA 2000).

The three-zone buffer scheme for agricultural areas is typically designed to maximize filtering of pollutants through surface and subsurface runoff (USDA 2000). On an agricultural site in the southeast, a study by Lowrance and Sheridan (2005) examined surface runoff through a three-zone buffer system that totaled approximately 75 m in width. The complexity of the environmental variation related to slope, soil conditions, and water transport between vertical and horizontal gradients makes it difficult to assess the performance of the buffer if zones are analyzed independently of each other. Instead, the authors evaluated the effectiveness of nutrient removal across the entire span of the three zones and determined the buffer decreased nutrient loads delivered from adjacent agricultural fields (Lowrance & Sheridan 2005).

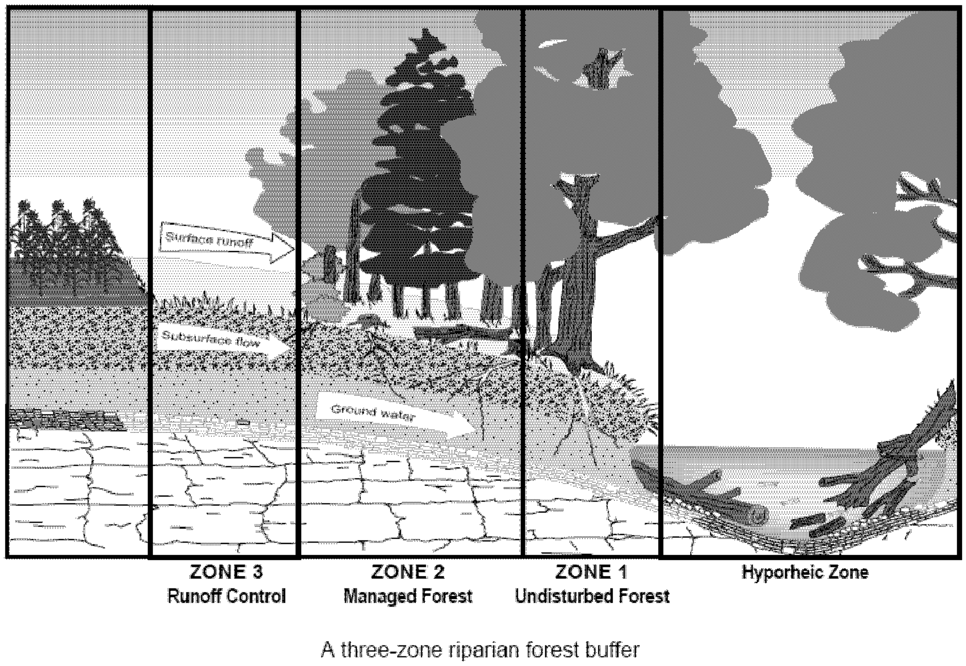


**Figure 4.** USDA three-zone buffer system (from, USDA 2000)

The prospect of modeling agricultural riparian processes offers an alternative to conducting large-scale environmental manipulative experiments. The riparian ecosystem management model (REMM) was developed based on the three-zone agricultural buffer system with the intent of creating a tool whereby managers could examine the implications of various design parameters on the effectiveness of riparian buffers (Lowrance et al. 2000). Comparing model simulations to observed conditions revealed some discrepancies, but overall, the model sensitivity faired well. Models designed specifically for examining the fate of pesticides in agriculture-riparian interfaces have also demonstrated positive potential (Lin et al. 2002, Probst et al. 2005). Despite the encouraging potential offered by these models, as long as experimentation is unable to provide a clear understanding of functional processes as they relate to agricultural buffers, the capabilities of predictive models will be bleak (Dosskey 2002). Variability across multiple spatial scales may require a great deal of fine tuning before model simulations are able to systematically predict variables, such as appropriate width and vegetation requirements, for agricultural buffers.

## 5.0 Conservation Reserve Enhancement Program

In Washington and Oregon, inception of the CREP began in 1998 as a voluntary program designed to promote healthy riparian habitats in agricultural areas (Figure 5). CREP activities are managed jointly by the state and the U.S. Department of Agriculture (USDA) Farm Service Agency (FSA). CREP is a voluntary program involving cooperation from farmers and landowners who sign 10- to 15-year lease agreements designating riparian corridors as conservation areas (Smith 2006). The program provides monetary compensation for participating landowners. During the contract period, designated CREP land may not be used for cultivation or livestock grazing (Smith 2006).

**Figure 5.** Examples of CREP Projects in Walla Walla County, eastern Washington. Riparian plantings are composed of multiple species of vegetation.

In Eastern Washington, the highest implementation of CREP projects has occurred in Walla Walla County, with nearly 3,000 acres of CREP riparian buffers (Smith 2006) (Figure 6). Projects implemented in eastern Washington are guided by functional objectives, including the improvement of water quality and in-stream habitat, with special consideration given to the potential benefits of restoring habitat conditions favorable to salmonids (Smith 2006). Statewide, roughly 78% of CREP projects are estimated to provide direct benefits to salmon (Smith 2006). In general, plant survival at Washington State CREP sites has been excellent, averaging 95% survival in eastern Washington (Smith 2006). Plant diversity at CREP sites is also generally quite high. Diversity within a riparian buffer is important because different plant types (i.e., trees versus grasses) have different functions and levels of effectiveness.

A major drawback to the CREP program is the minimum area required to be placed in the lease agreement. At a minimum, buffers are to achieve a size threshold equal to 30% of the active floodplain (Smith 2006). The maximum buffer width that can receive a CREP rental payment is 180 feet, based on average buffer width. Natural Resources Conservation Service (NRCS) standards must be used in restoring riparian vegetation within the CREP buffer (Smith 2006).

Landowners of small farming operations are likely constrained by the current minimum width requirements of 35 to 100 feet. Smith (2006) asserts that participation in CREP programs would likely increase if the minimum buffer widths were set at the lowest end of the range (35 feet). The cumulative effect of having a larger quantity of CREP participants with smaller buffers may prove more beneficial than fewer projects boasting large, discontinuous riparian buffers (Smith 2006). Based on current riparian research, a 30- to 50-foot buffer on a low-gradient slope could provide much of the functional value of a native riparian area for streambank stabilization, sediment and nutrient filtering (water-quality function), moisture retention, and OM input. This width of buffer, however, would only provide about half the function for shade (temperature regulation) and LWD recruitment, and only a fraction of the wildlife habitat functional value (Smith 2006).

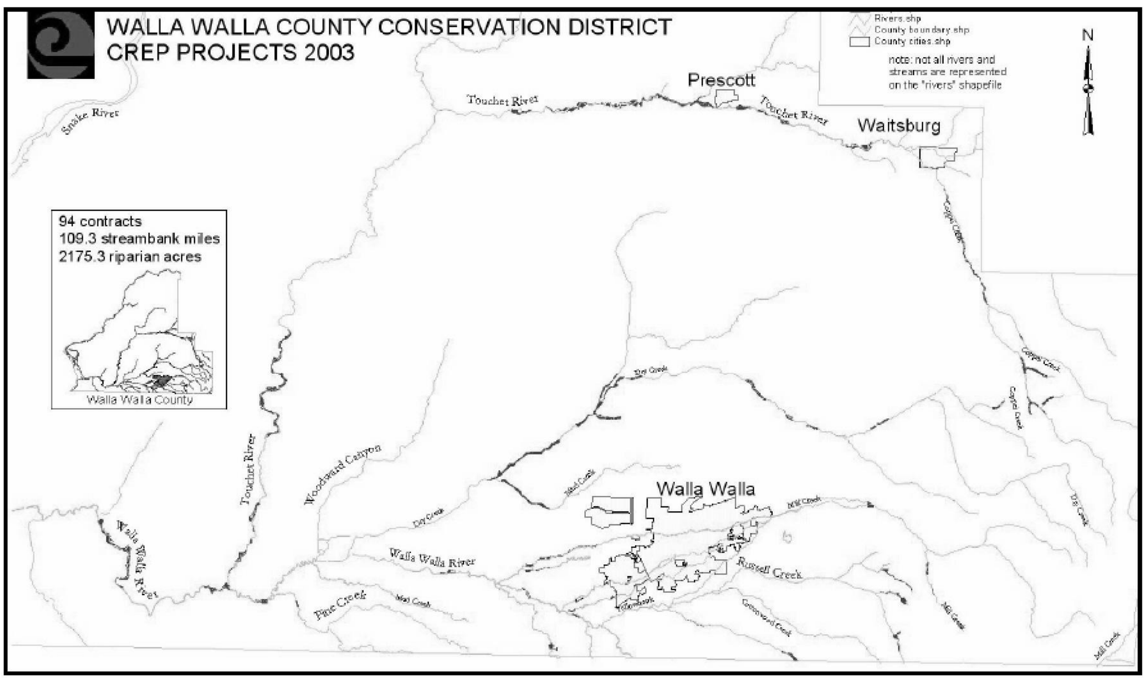


**Figure 6.** CREP Projects in Walla Walla County, Washington (Walla Walla Watershed Planning 2006).

## 6.0 Agricultural Practices

Agricultural practices such as row-cropping can be implemented such that agricultural runoff gradually infiltrates and/or filters through the riparian buffer zone before reaching a stream, lake, or wetland (NRC 2002). However, in some cases, this type of agricultural best management practice (BMP) is not implemented, and runoff is allowed to enter the water body without filtration. Elevated flow velocities of surface agricultural runoff can increase streamside erosion. Additionally, bypassing the filtration process through the riparian buffer can result in degraded water quality (NRC 2002).

The direction of crop placement can influence the effectiveness of buffers intended to avert pollutants from streams. Patty et al. (1997) found that grass buffers reduced suspended solids by 58% when wheat was sown perpendicular to the slope compared with crops planted parallel to slopes. In the Yakima River basin, a primary factor influencing the occurrence of agricultural pollutants in surface waters is the use of rill irrigation practices (Fuhrer et al. 2004). Converting these practices to less-erosive options such as drip or sprinkler irrigation has led to reductions in phosphorus; however, nitrate levels have yet to follow (Fuhrer et al. 2004).

Livestock grazing can also negatively affect riparian vegetation through physical degradation and resulting changes in riparian functional processes (Armour et al. 1991, Belsky et al. 1999). Loss of vegetation and soil disturbance influences biogeochemical processes and creates favorable conditions for the proliferation of exotic species in riparian areas (NRC 2002). In addition, trampling by livestock causes high rates of erosion, which results in channel incision that ultimately lowers the water table (Belsky et al. 1999). Vegetative losses degrade water quality and increase stream temperatures. Arid areas are particularly sensitive to vegetative removal, because increases in stream temperature can be detrimental to fish populations (Armour et al. 1991). The cascading effects to stream ecosystem processes as a consequence of grazing pressure within riparian areas compromises habitat for fish and wildlife (NRC 2002). In the Blue Mountains of northeastern Oregon, the combination of grazing by wild ungulates and sheep herds diminished the growth and reproduction of riparian willows (Brookshire et al. 2002). Improved grazing management can minimize the impact to stream systems. Sites that are rotationally grazed offer better water quality for aquatic biota through reduced levels of coliform, turbidity, and percentage of fine sediment, than do sites that are continuously grazed (Sovell et al. 2000).

## 7.0 Summary of Riparian Research

Numerous studies have been conducted throughout the world in an attempt to quantify the effectiveness of riparian management areas and buffers in protecting aquatic resources. Despite this extensive research, much remains that is not fully understood about stream-riparian ecosystem functions and the utility of riparian "buffers" in protecting ecological integrity. This is not surprising considering the natural variability of aquatic and terrestrial ecosystems and the complexity of stressors affecting them. Much of the riparian research has focused on forested areas, but a substantial body of research does exist on the use of riparian buffers in agricultural settings. Existing agro-riparian research has focused on the role of buffers as a means to maintain water quality by filtering pollutants (e.g. sediments, nutrients, and pesticides). This review of agro-riparian literature did not uncover significant sources of empirical data related to the efficacy of buffer widths and the ecological functions of riparian zones (e.g. microclimate, the input of organic material, and fish and wildlife habitat). Although only a few riparian buffer studies have been conducted in the interior Columbia River basin the findings of other studies can be applicable to the region.

One of the most common difficulties in trying to develop a recommendation for establishing appropriate riparian buffer specifications using the most current research available is that most studies only examine a few selected buffer widths, under specific environmental conditions, and typically for only one external stressor. Most of these studies tend to draw conclusions on "effective" buffer widths as a byproduct of their sampling design rather than deriving it experimentally. Based on this caveat, the research findings presented in the following section should be used with caution and only when they meet the conditions applicable to the site in question.

We present here the research findings applicable to the interior Columbia River basin with respect to riparian function. The most commonly recognized ecological functions of the riparian corridor include the following:

- Maintaining water quality by filtering and vegetative uptake of nutrients and potential anthropogenic pollutants from groundwater and surface runoff
- Stabilizing streambanks and minimizing streambank erosion; reducing fine sediment input into the stream system through floodplain retention and vegetative filtering
- Providing canopy-cover shade necessary to maintain cool stream temperatures and regulating microclimate in the stream-riparian corridor, a critical function for cold-water stream habitats.
- Providing a source of coarse particulate organic matter (CPOM) and LWD into the stream channel: LWD is an important instream structural element, which functions as a hydraulic roughness element to moderate stream flows; CPOM also provides organic carbon for the base of the aquatic food web
- Providing critical wildlife habitat, including migration corridors, feeding and watering habitat, and refuge areas during upland disturbance events.

## 8.0 Water Quality

The degradation and removal of riparian vegetation, combined with agricultural practices, has had a deleterious effect on the water quality of streams and rivers in eastern Washington (Williamson et al. 1998, Fuhrer et al. 2004). In the Central Columbia Plateau region, adverse instream water-quality conditions are largely a result of agricultural practices (Williamson et al. 1998). The lack of historical levels of riparian vegetation, combined with agricultural impacts, has led to the presence of fertilizers, pesticides, and sediment in surface waters. Historically, grazing pressure also adversely affected stream areas. However, agriculture has become the dominant form of land use, resulting in more localized grazing pressure (Williamson et al. 1998).

Other agricultural areas plagued by similar circumstances have also degraded water quality as a result of increased sediment delivery, nutrients, and pesticides into streams (NRC 2002). Based on the scientific literature reviewed, it is apparent that riparian vegetation can mitigate some of the adverse impacts caused by land-use activities. However, the degree to which riparian areas function in this capacity is dependent not only on the intensity of the land-use activities, but also on the characteristics of the riparian zone. Soil type, hydrology, slope, vegetation type, and the overall width of the buffer all determine the capacity of the riparian area to mitigate adverse impacts to adjacent receiving waters (Correll 1997, Wissmar 2004, Dosskey et al. 2005).

In general, the effectiveness of riparian areas at removing pollutants is largely dependant on soil conditions and surface and subsurface hydrology. Healthy soils directly contribute to healthier water resources by storing water and nutrients, regulating the overland flow of water, and filtering, immobilizing, and degrading pollutants (Morris & Moses 1999). Soil is composed of many components, including inorganic mineral particles of various sizes (clay, silt, and sand), OM in various stages of decomposition, and many species of living organisms. Healthy soils are vital in the establishment and nourishment of plants and provide habitat for millions of organisms. Areas with natural vegetation cover and leaf litter provide OM to the soil and usually have high infiltration rates (May 2003). Water that is stored in soil is slowly discharged to the stream through subsurface flow.

Surface runoff characterized by low-velocity, sheetflow is more easily filtered and adsorbed by riparian areas than is concentrated, high-velocity runoff (Correll 1997). In areas where shallow groundwater is dominant, the riparian root zone is able to maintain contact with subsurface flow, whereby pollutants are more readily adsorbed. However, the connection between groundwater and riparian vegetation is lost in areas dominated by deeply incised channels (Correll 1997). Clay-based soils, coupled with high water tables, often create pathways that readily transport pollutants from agricultural fields into streams (Parkyn 2004). Slope, soil permeability, and the size of the contributing area are also factors related to the efficiency of buffers used as water-quality filters in agricultural areas (Dosskey et al. 2005). Research has also attributed the magnitude of stream erosion to the type of vegetation planted in buffers (Zaimes et al. 2004).

Soil quality is typically degraded in riparian corridors where land-use activities often include removal of natural riparian vegetation, compaction of soil, and placement of fill (May 2003). Soil compaction reduces water infiltration and contributes to water runoff (Morris & Moses 1999). Pollutants such as nutrients, metals, petroleum hydrocarbon compounds, and organic chemicals (pesticides, herbicides, and industrial chemicals) are commonly found in stormwater and agricultural runoff. Most of these pollutants can be found in both the dissolved and particulate forms. The dissolved form tends to be the most bioavailable form, but the bulk of pollutants usually are in the particulate form (Pitt et al. 1995). Therefore, removal of fine sediment and OM often removes a large percentage of the pollutant load as well (Karr & Schlosser 1977, Peterjohn & Correll 1984, Osborne & Kovacic 1993). Changes in water chemistry can result in pollutants changing from particulate to dissolved form (i.e., metals adsorbed to particulates can become soluble as pH changes).

# 9.0 Sediment

Riparian vegetation provides natural streambank stabilization and control. Sediment delivered to receiving waters can originate from streambank erosion, from within the channel, from upland land-use activities (e.g., logging, construction sites, roads, grazing, and agricultural activities), and from natural disturbances (e.g., mass-wasting events, debris flows, and landslides). Sediment occurs naturally in any stream, but changes in the total sediment load and particle-size distribution that exceed natural levels due to human land-use activities can impose negative impacts on fish and other aquatic habitat (Chapman

1988). Fine sediment can typically originate in upland areas where bare soil is exposed to rainfall and runoff. Agricultural activities such as row-crop farming and livestock grazing can be significant sediment sources. Once fine sediment enters the stream system, it can remain in the channel for an extended period or be flushed rapidly through the system (Lowrance et al. 1984).

The physical structure provided by riparian vegetation slows runoff, mechanically filters and stores fine sediment, and holds materials in place (Swanson et al. 1982, Gregory et al. 1991, Knutson & Naef 1997, Naiman & Decamps 1997, Naiman et al. 2000). This process may also facilitate natural streambank maintenance as sediment is deposited on the streambank and floodplain, changing channel morphology (Fetherston et al. 1995, Abbe & Montgomery 1996, Rot et al. 2000). Natural floodplains are important as sites for sediment deposition and retention (Kauffman et al. 1997).

In research studies to date, a wide range of buffer widths have been noted to be effective in sediment trapping and removal. Much of this variation is likely due to differences in vegetation type/quality, differences in slope, and soil types used in the research studies. In general, the ability of a riparian buffer to remove fine sediment from runoff is a function of buffer width, soil type, side-slope gradient, local topography, and vegetation conditions. In addition to vegetation differences, however, variability in measurement techniques can preclude comparisons between multiple data sets. Some studies use a gross measure of sediment, whereas others monitor turbidity or total suspended solids (TSS) (Desbonnet et al. 1994). One of the biggest variations among studies is whether natural riparian vegetation or some form of cultivated vegetation was used in the test. The most frequent example involves the use of grass VFSs to treat runoff from agricultural areas.

The filtering, trapping, and deposition of sediment within riparian buffer zones are most influenced by the slope of the contributing area and the ability of the buffer to filter material delivered as surface or overland flow (Correll 1997). The success rate of these processes is largely dependent on the velocity and characteristics of the surface runoff. Sheetflows and low-velocity flows generally yield higher rates of deposition and filtration (Correll 1997, Dillaha & Inamdar 1997). Most natural riparian forests have the capacity to intercept and retain sediment transported from adjacent agricultural fields (Cooper et al. 1987). Some studies have demonstrated that sediment removal by riparian areas is proportional to the length of the vegetative filter flow-path (Daniels & Gillliam 1996).

The use of VFSs is often used as an alternative management approach when native riparian plantings are not possible or when large-scale riparian restoration projects are not feasible. The use of VFSs has proven to be successful in diffusing pollutants before they enter nearby waterways. The results of Dillaha and Inamdar (1997) point out that VFSs are effective at sediment removal when overland flow is uniform. To ensure VFSs remain functional as sediment filters, it is necessary to monitor these structures and to perform periodic maintenance (e.g., sediment removal and revegetation). Frequent maintenance of VFSs may be necessary to ensure effectiveness does not decrease through time. Maintenance and precautionary actions include mowing, physical removal of accumulated sediment, exclusion of livestock, careful application of herbicides adjacent to the VFS, and the construction of drainage areas parallel to the VFS (Dillaha & Inamdar 1997). In Dillaha et al. (1989), the effectiveness of a VFS to trap and retain sediment was found to decrease through time as the vegetative area becomes inundated with sediment. A similar study Robinson et al. (1996), however, found no evidence that the filtering capability of the VFS decreased with time.

The effectiveness of filtering sediment by VFSs has been tested under many experimental conditions. Most studies are aimed at finding the minimum width required to provide the most adequate degree of protection for streams. The problem with comparing the results of these studies is that most are conducted under different spatial and temporal scales. Some apply variable width treatments testing multiple vegetative species, whereas others maintain these as constants to investigate parameters such as pollutants or slope. Under laboratory conditions, the length of Kentucky bluegrass filter strips was deemed an important factor with regard to sediment filtration, whereas the height of the grass was not necessarily a significant factor related to the interception of sediment (Pearce et al. 1997).

Similarly, a study by Mickelson et al. (2003) found the length of a VFS to influence the effectiveness of sediment removal. This laboratory study examined a VFS comprised of smooth brome grass, Kentucky bluegrass, and Kentucky tall fescue at two widths: 4.6 m and 9.1 m. Although the 4.6-m strip reduced sediment by 71%, the 9.1-m VFS reduced sediment by 87.2% (Mickelson et al. 2003). The results of an experiment designed to test the sediment filtering capacity of 18.3-m bromegrass filter strips under different slope conditions determined that soil loss was greater on a 12% slope than on a 7% grade (Robinson et al. 1996). This study revealed that under natural rainfall conditions, sediment was most effectively trapped within the first 3 m of the strips and sediment removal beyond 9.1 m was negligible under both slope conditions (Robinson et al. 1996). Results of Dillaha et al. (1989) also noted the first few meters of the strip appear to be the most effective at trapping sediment.

Many attempts have been made to quantify differences in the effectiveness of VFSs and multi-species riparian buffers. In a Nebraskan research facility, Schmitt et al. (1999) designed an experiment to test both width and buffer type with regard to the filtration of pollutants. Vegetative treatments were planted at either 7.5-m or 15-m widths and consisted of 1) mixed grasses, 2) a mixture of grasses, shrubs, and trees, and 3) pasture. Statistical analysis revealed width had more of an impact on filtration than did vegetative treatments. The 15-m widths were 85% effective at TSS removal, compared with 77% for the 7.5-m widths. In an agricultural area in Iowa, a study by Lee et al. (2003) compared 1) no buffer, 2) a 7-m switchgrass buffer, and 3) a 16.3-m grass-wooded buffer. Under natural rainfall conditions, the grass and grass-wooded buffer treatments removed 92% and 97% of the sediment, respectively (Lee et al. 2003).

Several factors must be considered when determining the most appropriate buffer width for sediment filtering. Relatively narrow buffers may be acceptable for intercepting sand or large OM particles; however, they may not function in the same manner if clay-based soils are present (Cooper et al. 1987). A study by Daniels and Gilliams (1996) determined that VFSs were more effective at removing sand than silt fractions. Comparing the filtering capacity of grass buffers with buffers composed of grass-wooded vegetation, conclusions in Lee et al. (2000) stated the grass-wooded buffers removed a higher percentage of clay (52% to 89%) than did the buffer composed only of grass (15% to 49%). Although this study concluded the buffer containing woody vegetation removed a higher proportion of fine sediment, it is important to note the wooded buffer (16.3 m) was more than twice the length of the grass buffer (7.1 m). In a later study conducted by Lee et al. (2003), results once again demonstrated that compared with non-buffered treatments, both grass and grass-wooded buffers were more efficient at reducing sand fractions.

In southeastern Minnesota, sedimentation under different buffer types and under different grazing pressures examined through a study by Sovell et al. (2000). Researchers found that grass buffers were more effective at filtering fine sediment than were wooded riparian areas. However, interpreting results from Sovell et al. (2000) should include careful consideration of the site conditions. The high percentage of fine sediment associated with the wooded riparian areas may have been heightened by the relatively steep slopes and sparse understory vegetation (Sovell et al. 2000). Although it is apparent that buffers composed of grass or a combination of grass and woody vegetation retain sediment particles, the relationship between the functional response of buffers and the partitioning of particle size has yet to be fully quantified. A summary of the results of studies conducted to assess the effectiveness of agricultural buffers in the removal of sediment is represented in Table 1.

As noted above, the use of VFS buffers to treat runoff has merit, but this treatment should be done outside the boundaries of the stream-riparian ecosystem. In general, a VFS provides little habitat benefit, even though it can be quite effective as a water-quality BMP. Controlling input of sediment into the stream channel by preventing excessive streambank erosion and filtering runoff represents one functional process of riparian areas; however, it is not the only function. In fact, in naturally forested watersheds, the need for sediment filtration is fairly infrequent and episodic. In contrast, agriculture, timber harvest, road maintenance, and construction tend to produce fairly high levels of sediment for extended periods. The best defense against fine sediment loading into the stream channel is prevention of bare soil exposure and minimization of transport of sediment at the source. Erosion and sediment control BMPs for agriculture and construction are well understood and relatively easy to accomplish.

## 10.0 Nutrients

The most common chemical pollutants found in agricultural runoff are nutrients. Excess nitrogen (N) and phosphorous (P) are generated from the application of fertilizers to agricultural fields or from livestock manure runoff. Excessive levels of nutrients in receiving waters can cause eutrophication. Eutrophication is a process in which excess nutrients stimulate algal growth. When the algae dies, the decomposition process can reduce dissolved oxygen (DO) levels in a water body to levels that can be harmful or fatal to native biota. Algal growth can be so extensive that it becomes a nuisance, clogging irrigation-water intakes or causing drinking-water problems (Welch 1992).

As with sediment, riparian buffers have been shown to be effective in decreasing nutrient concentrations. However, unlike sediment, nutrients occur in both dissolved and particulate forms, which can be transported via surface and subsurface flow paths (Figure 7). In addition to transport pathways, the fate of nutrients is also dependent on its form and solubility properties. Soluble nutrients are primarily removed from subsurface pathways by vegetative uptake (Swanson et al. 1982, Kauffman et al. 1997, Naiman & Decamps 1997). Plants can store nutrients in the form of woody (long-term) and non-woody (short-term) plant material. Nutrients are released from dead OM by leaching and decomposition. Nutrient uptake also occurs during decomposition (Swanson et al. 1982). Microbial processes, including immobilization of nutrients, denitrification, and degradation of organic pollutants, may also reduce excess nutrients (Palone & Todd 1997). Denitrification is a key nitrate removal mechanism in many riparian areas (Naiman & Decamps 1997, Palone & Todd 1997, Naiman et al. 2000). Microorganisms take up or immobilize nutrients just as plants do, and these nutrients are re-released following the death and decomposition of microbial cells and are then stored in soil organic matter. Degradation of organic pollutants occurs as microorganisms consume organic compounds as food sources (Palone & Todd 1997). The process of denitrification can also remove soluble N, most commonly in anaerobic zones of wetlands (Parkyn 2004).

**Table 1.** Summary of the Effectiveness of Agricultural Buffers in Sediment Removal

| Author | Location | Buffer type | Width | Slope | Soil type | Hydrology | Summary |
|---|---|---|---|---|---|---|---|
| Daniels & Gilliam (1996) | North Carolina | fescue<br>fescue/riparian forest | 6 m<br>20 m | -- | sandy loam to clay and silt loam to silt clay | natural rainfall. | **Sediment:** 60%-90% reduction by the buffers<br>Sediment filtration was positively correlated with buffer distance/width. |
| Dillaha et al. (1989) | Virginia | no buffer<br>orchardgrass<br>orchardgrass | 0<br>4.6 m<br>9.1 m | 0-4% | silt loam | simulated runoff | **Sediment:**<br>The first few meters of the VFS were the most effective at trapping sediment.<br>Efficiency of the VFS decreased with time. |
| Lee et al. (2000) | Iowa | no buffer<br>switchgrass buffer<br>switchgrass buffer/woody buffer | 0<br>7.1 m<br>16.3 m | 5-8% | fine-loamy, mixed | simulated runoff | **Sediment:**<br>7.1-m buffer retained 70% of the sediment<br>16.3-m buffer retained >92% of the sediment.<br>The grass strips were effective, but the combination of multiple vegetation types and added length of the grass/wood buffer was more effective than the grass buffers. |
| Lee et al. (2003) | Iowa | no buffer<br>switchgrass buffer<br>switchgrass buffer/woody buffer | 0<br>7.1 m<br>16.3 m | 5-8% | fine-loamy, mixed | natural rainfall. | **Sediment:**<br>7-m buffer; >92% removal<br>16.3-m buffer; >97% removal<br>Buffer removal efficiencies were positively correlated with buffer length. |
| Mickelson et al. (2003) | Iowa | VFS<br>VFS | 4.6 m<br>9.1 m | 3-6% | fine-loamy | simulated rainfall | **Sediment:**<br>4.6-m strip; 70.5% reduction<br>9.1-m strip; 87.2% reduction |
| Pearce et al. (1997) | Wyoming; laboratory | Kentucky bluegrass<br>Kentucky bluegrass<br>Kentucky bluegrass | 12.5 cm<br>25 cm<br>50 cm | 9% | sandy loam | simulated rainfall | **Sediment:** larger widths were more effective at sediment removal |

**Table 1.** (contd)

| Author | Location | Buffer type | Width | Slope | Soil type | Hydrology | Summary |
|---|---|---|---|---|---|---|---|
| Rankins et al. (2001) | Mississippi | no buffer<br>big bluestem<br>eastern gamagrass<br>switchgrass<br>tall fescue | 30 cm | 3% | silt clay | natural and simulated rainfall | **Sediment:** Each of the grasses tested reduced sediment by at least 66%. |
| Robinson et al. (1996) | Iowa | Bromegrass | 18.3m | 7%<br>12% | silty-loam | natural rainfall. | **Sediment:** 12% gradients experienced greater sediment loss than the 7% slopes.<br>85% removal of sediment at 9.1m on both slope conditions. Beyond 9.1m sediment loss was negligible. |
| Syversen & Bechmann (2004) | Norway | mixed grasses | 5m | 14% | silty clay loam | simulated runoff | Sediment:<br>Average removal efficiencies were 62%. |
| Sovell et al. (2000) | Minnesota | grass buffer<br>wooded buffer<br>rotationally grazed buffer | -- | -- | -- | surface water (stream) | **Sediment:** grass buffers had a lower percentage of fine sediment than wooded buffers.<br>**Turbidity**: sites with grass buffers yielded lower turbidity than wooded buffers. |

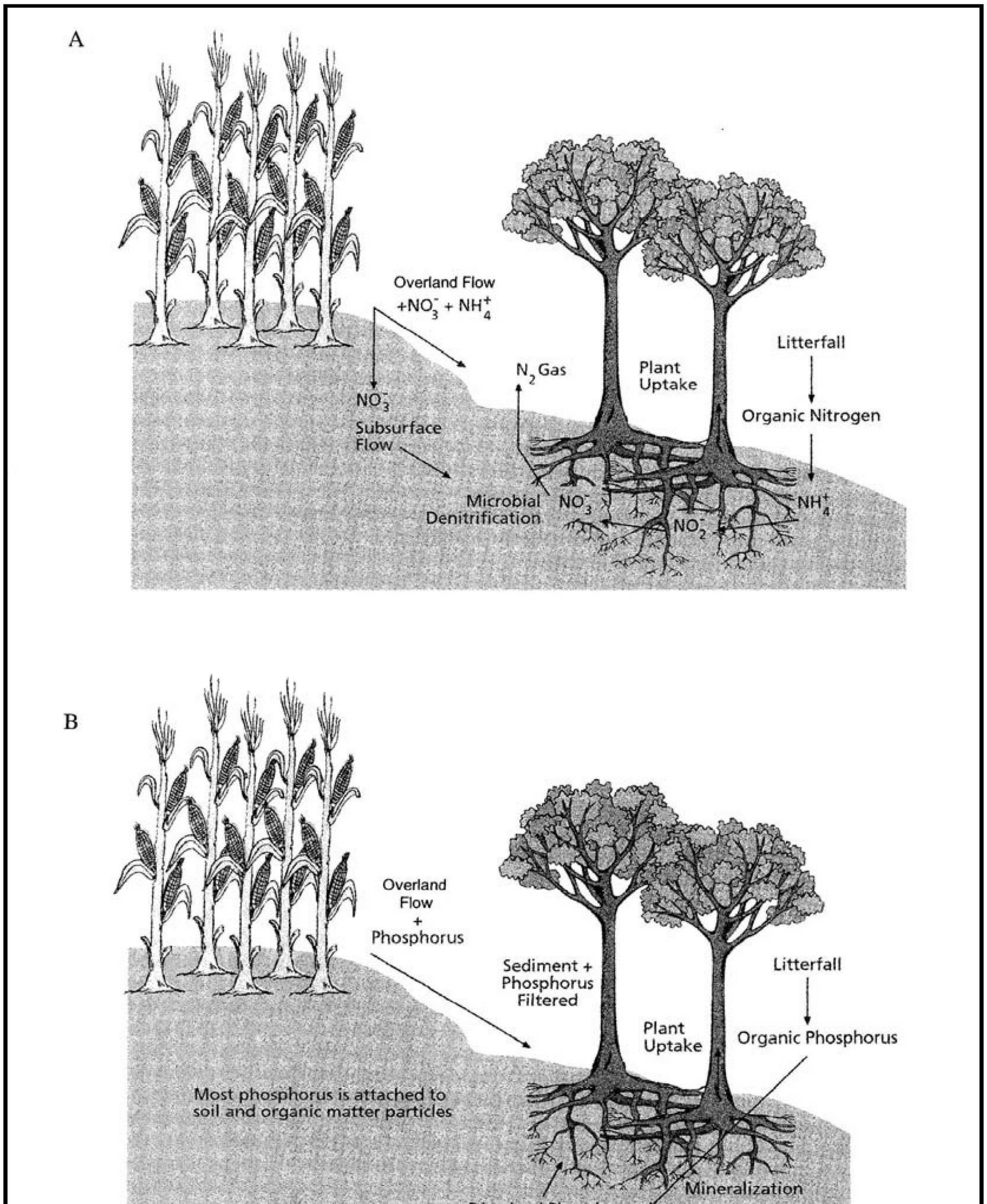


**Figure 7.** Fate and transport in riparian buffers for A) nitrogen and B) phosphorous (from NRC 2002).

## 10.1. Nitrogen

Generally, sediment-bound nitrogen is more readily removed by buffers than is inorganic nitrogen (Gilliam et al. 1997). There is some question regarding the longevity of nitrogen removal by buffers. Some believe the effectiveness of nitrogen removal by buffers may be hampered by continuous inputs from adjacent land-use activities (Gilliam et al. 1997). Although empirical data to support this hypothesis are not abundant, evidence suggests that nitrogen filtration by buffers may diminish with stand age (Mander et al. 1997).

Results are often unclear for studies combining width and vegetation variables. In these studies, nutrient reduction is achieved, but effectiveness is derived based on small-scale, controlled experiments. As demonstrated by Lowrance and Sheridan (2005), obtaining fine-tuned results at small scales is sometimes not achievable. Regardless, experiments attempting to determine the most appropriate width and vegetation type provide insight for managers, albeit the scope of these findings may be limited. Dillaha et al. (1989) showed VFSs can be used to reduce nitrogen and phosphorous generated from agricultural runoff. In this study, the overall length of the filter strip influenced the effectiveness of nitrogen removal; however, the relationship between VFS length and the removal of phosphorous was less apparent. Outside of the controlled field study, existing VFSs on agricultural lands were evaluated, and those bounded by sloped topography were deemed inefficient in nutrient removal (Dillaha et al. (1989). Other important variables include groundwater flow, soil characteristics, and biogeochemical processes (Gilliam et al. 1997, Mayer et al. 2005, Smith et al. 2006).

A meta-analysis of peer-reviewed literature showed that the effectiveness of nitrogen removal by grassy buffers was achieved by riparian zones 10 m to 50 m wide (Mayer et al. 2005, figures 8-14) (Figures 8 through 14). Based on the literature reviewed, this analysis also determined the efficiency of nitrogen removal by subsurface mechanisms to be greater than filtration through overland flow. Width was not the primary determinant of nitrogen removal effectiveness.

There is no clear consensus regarding the type of vegetation that is best for removing nitrates. Some studies indicate that forested buffers are best due to a deep rooting zone, whereas others show that grasses can play an equally if not more important role in nitrogen removal (Gilliam et al. 1997).

A study by Dhondt et al. (2006) investigated the efficiency of groundwater removal of nitrate by three existing riparian types: mixed vegetation, forest, and grass. The riparian vegetation that measured 60 m to 70 m wide was adjacent to pasture and arable lands. Groundwater nitrate measured 30 m from the agricultural lands was reduced by all riparian conditions, with removal efficiencies ranging from 72% to 100% (Dhondt et al. 2006).

Mander et al. (1997) compared multiple riparian vegetation types and stand age. This study determined that vegetation comprising grasses, shrubs, and young stand age trees were more effective at removing nutrients than were older stands of riparian forests. Soil attributes are also believed to play a role in nutrient retention in the study area, with phosphorous being more readily retained in the soil than nitrogen (Mander et al. 1997).

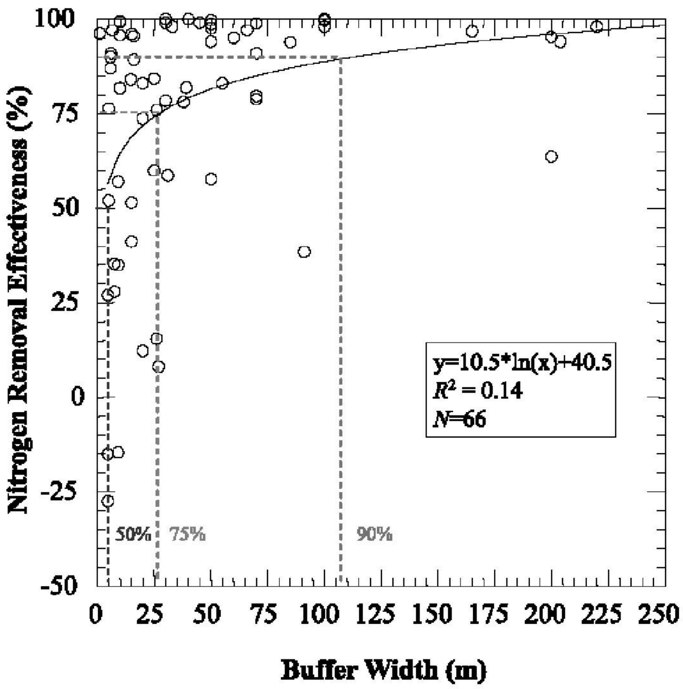


**Figure 8.** The relationship between nitrogen removal effectiveness and riparian buffer width. The 50%, 75%, and 90% nitrogen removal efficiency buffer widths are shown based on a fitted non-linear model (Mayer et al. 2005).

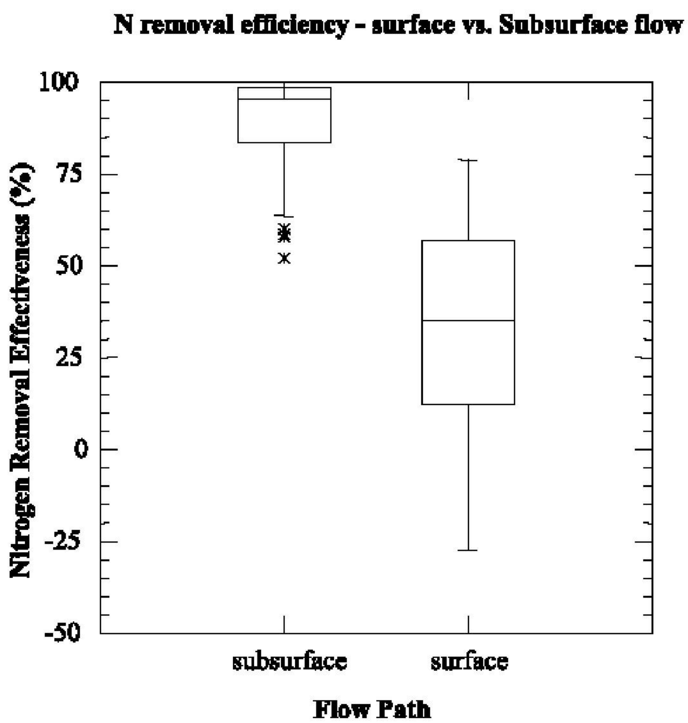


**Figure 9.** Nitrogen removal effectiveness in riparian buffers by flow path (Mayer et al. 2005).

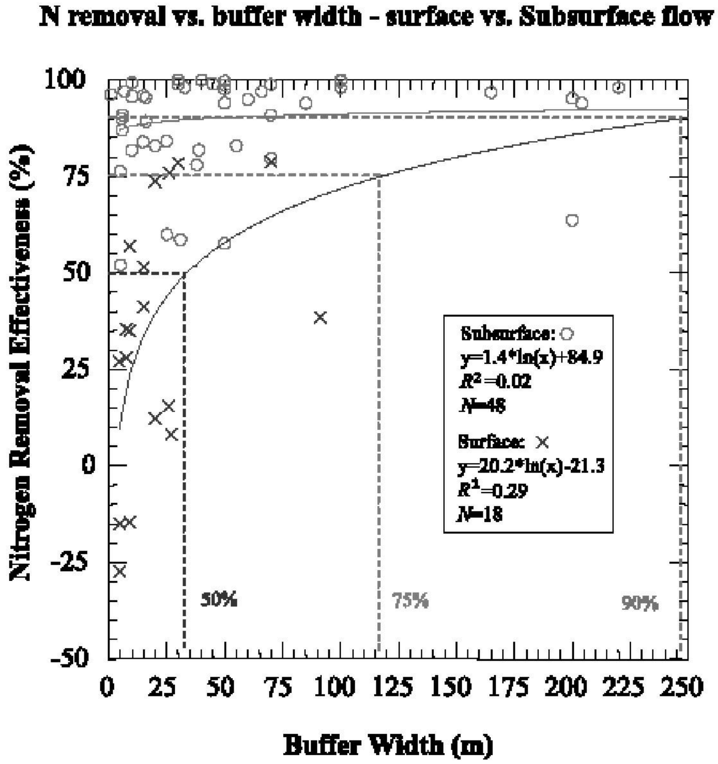


**Figure 10.** The relationship between nitrogen removal effectiveness and riparian buffer width by flow-path. The 50%, 75%, and 90% nitrogen removal efficiency buffer widths for surface flow-path are shown based on a fitted non-linear model (Mayer et al. 2005).

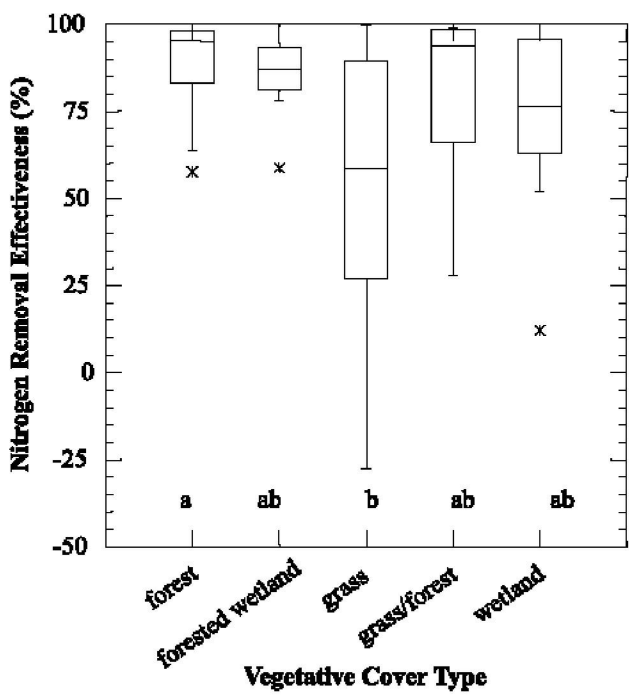


**Figure 11.** Nitrogen removal effectiveness in riparian buffers by vegetation type (Mayer et al. 2005).

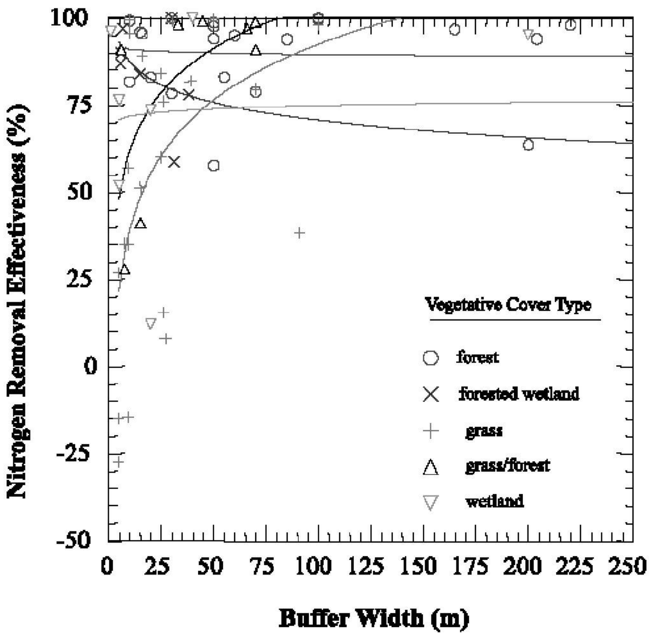


**Figure 12.** The relationship between nitrogen removal effectiveness and riparian buffer width by vegetation type. Curves are fitted to a non-linear model (Mayer et al. 2005).

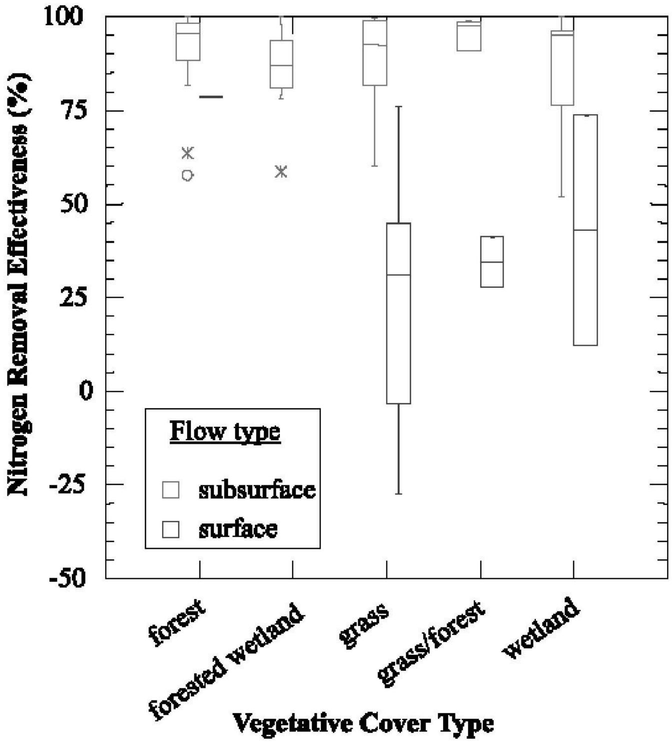


**Figure 13.** Nitrogen removal effectiveness in riparian buffers by vegetation type and flow-path (Mayer et al. 2005).

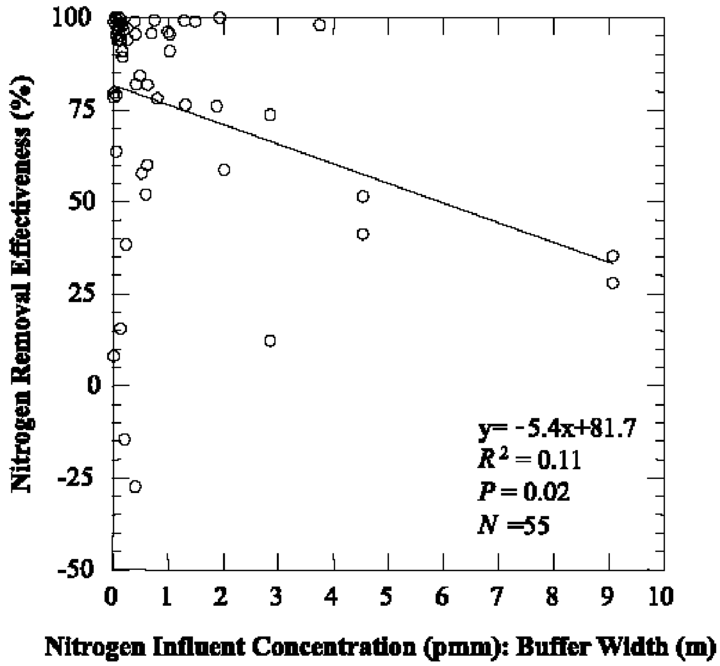


**Figure 14.** The relationship between nitrogen removal effectiveness and nitrogen-load:riparian-buffer-width ratio. Curves are fitted to a linear model (Mayer et al. 2005).

The use of variable widths and various types of vegetation as experimental parameters has produced a range of results. Some studies have arrived at the same conclusion: wider buffers are more effective, regardless of vegetation type. Other studies have demonstrated that vegetation type is the key component in the removal of pollutants. In Schmitt et al. (1999), three different treatments of riparian vegetation were tested at two separate widths. The study ultimately determined that width was a greater factor for the removal of contaminants than were vegetative treatments. Specifically, vegetation treatments were not correlated with nitrate-nitrite concentrations, and treatments of grasses and grass-shrub-trees yielded similar results with regard to contaminant reduction capacity (Schmitt et al. 1999).

In Osborne and Kovacic (1993), an experiment was designed to test the effectiveness of forested riparian areas compared with that of VFSs in an Illinois watershed. Results indicated that the VFS buffers were effective at reducing concentrations of nitrate-nitrite in shallow groundwater before it enters a stream, but the riparian forests were more effective at removing nitrate-nitrite from subsurface water (Osborne & Kovacic 1993). Interestingly, the width of the riparian forest in the Osborne and Kovacic (1993) study measured 16 m, whereas the grassed buffer was 39 m. Width also influenced the efficiency of nutrient removal of grass and grass-woody buffer on a farm in Iowa. In Lee et al. (2003), a 13-m grass-woody buffer was determined to be 20% more efficient at removing soluble nutrients than was a 7-m switchgrass buffer. The authors suggest larger, multi-species buffers are more effective and functionally different than are smaller, single-species buffers (Lee et al. 2003).

Hydrology and soil characteristics can also influence the degree to which nutrients are able to infiltrate groundwater sources from nearby agricultural fields. Depending on the groundwater dynamics of a given area, riparian zones may or may not intercept groundwater contaminants before they enter a stream or river system (Gilliam et al. 1997). Agricultural forested buffers designed using the three-tiered approach have been shown to effectively decrease groundwater nitrate; however, in areas where the subsurface flow is not in contact with the riparian vegetation, groundwater nitrate will not be minimized (Lowrance et al. 1997). Soil condition also influences the filtration rates of groundwater through riparian zones. Riparian vegetation associated with till tends to filter contaminants more effectively than does vegetation on sandy substrates because of the prolonged residence time of groundwater through till (Simpkins et al. 2005). Despite these possibilities, many studies have provided evidence demonstrating that buffers situated between agricultural stream interfaces are effective at trapping nutrients in groundwater systems.

In Lowrance et al. (1984), healthy riparian areas were demonstrated to be able to infiltrate groundwater nutrients generated from nearby row crops. Filtration of these nutrients by the riparian zones effectively buffered streams, preventing diminished water quality. In Maryland, nitrogen flux between corn fields and riparian forests spanning 50 m was found to occur by means of groundwater flow (Peterjohn & Correll 1984). The riparian forests retained 89% of the nitrogen, compared with adjacent croplands, which retained only 8%. A comparison of groundwater nitrate-nitrogen concentrations in the northeast yielded higher concentrations in corn fields than in nearby riparian areas (Young & Briggs 2005). Furthermore, forest buffers maintained lower concentrations of nitrate-nitrogen than did grass buffers. However, Young and Briggs (2005) states that soil type and depth of the water table are the primary determinants of groundwater denitrification in this northeastern study. Along the coastal plains of North Carolina, increasing the buffer width from 9 m to 30 m was correlated with decreasing concentrations of nitrate in a shallow groundwater farm site. Nitrate reductions from field to stream ranged from 35% to 53% in the 9-m buffer and increased to 93% to 95% reduction with the wider buffer zone (Smith et al. 2006). As with other studies reviewed, a detailed analysis of these results indicate the complexity of groundwater-riparian dynamics are not easily attributed to a single factor. Concentrations of organic carbon and groundwater flow paths also play a role in the fate of nitrate transport and reduction within riparian areas (Smith et al. 2006).

### 10.2. Phosphorous

Inherent differences in the chemical properties between nitrogen and phosphorous lead to different transport mechanisms by which these chemical compounds travel through riparian areas. Similar to sediment and nitrogen, phosphorous concentrations are also decreased by riparian vegetation. Phosphorous is typically sediment-bound, which in some cases allows it to be more easily retained by buffer vegetation than is dissolved nitrogen (Schmitt et al. 1999). By investigating the transport of nutrients in overland and subsurface flow, Peterjohn and Correll (1984) noted nitrogen flux occurred by means of groundwater flow, whereas phosphorous delivery into riparian forests occurred mainly through surface runoff. Because of the association between phosphorous and sediment, management goals aimed at reducing sediment transport from arable lands will also tend to minimize phosphorous loads in surface waters (Palone & Todd 1997).

The type of vegetation found in riparian buffers can also enhance the adsorption of phosphorous. Native vegetation attributed with deep root structures is usually most efficient at intercepting runoff, reducing water velocities, filtering sediment, and reducing phosphorus loading in riparian buffers (Uusi-Kamppal et al. 1997). The characteristics of native vegetation generally create favorable conditions for intercepting particulate phosphorous before it is transported to nearby water bodies. The width of riparian buffers can also enhance vegetation effectiveness for phosphorous removal. A study by Osborne and Kovacic (1993) compared the phosphorous removal efficiency of two grass species and determined that a 20-m buffer of oats was insufficient at reducing total phosphorous from surface water runoff, whereas a buffer composed of rye grass was able to achieve reductions at half the width. Conditions favorable to buffer removal of particulate phosphorous do not always hold for dissolved phosphorous.

Although most researchers agree that riparian areas provide functional benefits to streams by filtering nutrients, there can be disagreement about the degree to which this occurs. In Parkyn et al. (2005) modeling techniques were used to simulate the effect of riparian buffers on stream nutrient levels. Results indicate that riparian plantings along large streams can, in some cases, lead to an increase in nutrient export. In addition to increasing nutrients within the stream, this study found that riparian restoration in pasture lands caused an increase in sediment yield (Parkyn et al. 2005). The exact reason for these results was not determined, but it does show that unique site characteristics can affect buffer effectiveness. As is the case with sediment filtering, the site-specific nature (e.g., soil type, vegetation type, slope, and other factors) of buffer effectiveness in removing nutrients from agricultural runoff is a significant point of emphasis. A summary of the results of research investigating the effectiveness of nutrient filtration by buffers in agricultural lands is provided in Table 2.

### 10.3. Pesticides

The Central Columbia Plateau and the Yakima River Basin were selected as study units for the U.S. Geological Survey (USGS) National Water Quality Assessment Program in 1992 and 1999, respectively. The studies identified water-quality concerns by examining nutrients, sediment, and pesticides in surface and groundwater sources within these regions. Although these studies did not correlate water-quality results with riparian condition, each acknowledged poor water quality and that instream habitat conditions were linked to the degradation of riparian vegetation, as compared with historical conditions (Williamson et al. 1998, Fuhrer et al. 2004). Appendix B contains a summary of pesticide data from these two USGS studies. Appendix C lists crops and associated pesticides and herbicides common to the Yakima Basin.

The primary forms of agriculture in the interior Columbia River basin include wheat, potatoes, corn, and orchards. Pesticides detected in surface waters in this region were detected most frequently in irrigated agricultural areas (Williamson et al. 1998). Conversely, in areas where dry-land farming is prevalent, pesticides were detected at much lower levels (Williamson et al. 1998).

The USGS study in the Yakima River Basin showed similar trends. Throughout the Yakima Basin study area, pesticides were detected at lower frequencies in regions dominated by hay and pasture (e.g., dry-land farming) than they were in areas exhibiting more diverse cropping practices (Fuhrer et al. 2004). Despite the recent discontinued application of many organochlorine compounds to agricultural areas in the region, erosive processes have continued to carry these pollutants into waterways where they are still detected in sediment and fish tissues (Munn & Gruber 1997).

In areas of the interior Columbia River basin dominated by agriculture, herbicides were also commonly detected in surface waters and groundwater. Detections during the non-irrigation season were typically lower than during the peak of the growing season when irrigation is more heavily used (Williamson et al. 1998). However, this general trend was not maintained in the Yakima Basin, where insecticides were not commonly detected during non-irrigation season (Fuhrer et al. 2004). Each of the USGS studies in Eastern Washington detected a range of pesticides in both surface and groundwater systems. Some were detected at levels exceeding the criteria for chronic freshwater toxicity (Table 3).

**Table 2.** Summary of Reviewed Documents Investigating the Effectiveness of Nutrient Filtration by Buffers in Agricultural Settings

| Author | Location | Buffer type | Width | Slope | Soil type | Hydrology | Nutrients | Summary |
|---|---|---|---|---|---|---|---|---|
| Daniels & Gilliam (1996) | North Carolina | fescue | 6 m | -- | sandy loam to clay and silt loam to silt clay | natural rainfall | nitrogen | **Nitrate:** 35%-60% reduction |
| | | fescue/riparian forest | 20 m | | | | phosphorus | Phosphorous: 60% reduction |
| Dhondt et al. (2006) | Belgium | grass | 60-70 m | <2%-15% | NA | groundwater | nitrate | ***Grass buffer;*** 97%-100% efficient at $NO_3$ removal. |
| | | mixed vegetation | | | | | | Mixed vegetation; 92%-100% efficient |
| | | forest | | | | | | ***Forest buffer;*** 72%-90% efficient |
| Dillaha et al (1989) | Virginia | no buffer | 0 | 0%-4% | silt loam | simulated runoff | | |
| | | orchardgrass | 4.6 m | | | | nitrogen | **Nitrogen**:<br>4.6 m VFS; 63% nitrogen reduction<br>9.1 m VFS; 76% nitrogen reduction |
| | | orchardgrass | 9.1 m | | | | phosphorus | **Phosphorus:**<br>4.6 m VFS; 49%-85% phosphorus<br>9.1 m VFS; 65%-95% phosphorous reduction |
| Lee et al. (2000) | Iowa | no buffer | 0 | 5%-8% | fine-loamy, mixed | simulated runoff | | The grass strips were effective, but the combination of multiple vegetation types and added length of the grass/wood buffer was more effective than the grass buffers. |
| | | switchgrass buffer | 7.1 m | | | | nitrogen | **Nutrients:** |
| | | switchgrass buffer/woody buffer | 16.3 m | | | | phosphorus | 7.1-m grass buffer; 44%-72% nutrient removal<br>16.3-m grass/woody buffer 80%-93% nutrient removal |
| Lee et al. (2003) | Iowa | no buffer | 0 | 5%-8% | fine-loamy, mixed | natural rainfall. | | The buffer removal efficiencies were positively correlated with buffer length. |
| | | switchgrass buffer | 7.1 m | | | | nitrogen | **Nutrients**: The narrower buffer was effective at sediment and sediment-bound nutrient removal, but the wider buffer increased the removal efficiency of soluble nutrients by 20% |
| | | switchgrass buffer/woody buffer | 16.3 m | | | | phosphorus | |
| Lin et al. (2004) | Missouri: laboratory greenhouse | orchard grass | NA | NA | sandy loam | simulated | nitrate | Compared with orchard grass and timothy, switchgrass, tall fescue, and smooth bromegrass yielded the most promising results for soil remediation nitrate |
| | | smooth bromegrass | | | | | | |
| | | tall fescue | | | | | | |
| | | timothy | | | | | | |

| Author | Location | Buffer type | Width | Slope | Soil type | Hydrology | Nutrients | Summary |
|---|---|---|---|---|---|---|---|---|
| Lowrance et al. (2005) | Georgia | switchgrass<br>grass strip;<br>managed forest<br>unmanaged forest | 8 m<br>45-60 m<br>15 m | 2.50% | loamy sand | Natural surface runoff | nitrogen and Phosphorous | **Nutrients:** the highest reduction of nutrients occurred in the grassed buffer strip |
| Mander et al. (1997) | Estonia | 14-year-old grey alder stand<br>40-year-old grey alder stand | 20 m<br>28 m | -- | -- | -- | nitrogen | **Nitrogen:** higher removal rates are achieved by buffers comprising multiple species and vegetative types. Shrubs and young trees are most effective. |
| Osborne & Kovacic (1993) | Illinois | row crops<br>riparian forest<br>reed canary grass buffer | 0<br>16 m<br>39 m | -- | silty clay loam | groundwater | nitrate<br>phosphorus | **Nitrate:** forested buffers were more effective at nitrate reductions than were grass buffers<br>**Phosphorous:** the grass buffer strip was more effective at P retention than was the forested buffer |
| Peterjohn & Correll (1984) | Maryland | 50m of riparian forest | 50 m | basin: 5% | fine sandy loam | groundwater and surface runoff | nitrogen and Phosphorous | **Nitrate:** forested buffers retained 89% of nitrogen<br>**Phosphorous:** forested buffer retained 80% of phosphorous |
| Schmitt et al. (1999) | Nebraska | grain sorghum<br>grasses<br>grasses-trees combined | 0<br>7.5 m<br>15 m | 6%-7% | silty clay loam | simulated runoff | nitrogen<br>phosphorus | **Width versus vegetation type**: buffer width is positively correlated to the efficiency of contaminant removal.<br>**Nutrients:**<br>Phosphorus was more effectively reduced by the buffer than nitrogen because of the high sorption of total phosphorous with sediment particles. |
| Schultz et al. (1995) | Iowa | switchgrass<br>shrubs<br>trees | 7 m<br>3.2 m<br>8-10 m | "gentle" | NA | groundwater | nitrogen | **Nitrate:** in each of the three zones, the multi-species riparian buffer zone is effective at reducing nitrate. |
| Smith et al. (2006) | North Carolina | mixed vegetation: grasses, shrubs, and trees | 9 m<br>30 m | -- | coarse-loamy | groundwater | nitrate | **Nitrate**:<br>9-m buffer; 35%-53% nitrate reduction<br>30-m buffer; 95%-93% nitrate reductions in shallow groundwater |
| Young and Briggs (2005) | New York | mixed grasses<br>salix-grass<br>forested riparian buffer | 9 m<br>9 m<br>10 m | 0%-6% | silt loam | groundwater | nitrogen | **Nitrogen:** soil type strongly influenced $NO_3$-N concentrations. Compared with grass buffer, forest buffers yielded the lowest $NO_3$-N concentration |

**Table 3.** Pesticides in the Central Columbia Plateau and the Yakima River Basin Detected at Levels that Exceed the National Guidelines for Protecting Aquatic Life (adapted from Williamson et al. 1998, Fuhrer et al. 2004)

| Pesticide (trade or common name) | Pesticide Type |
|---|---|
| Central Columbia Plateau | |
| Triallate (Far-go) | Herbicide |
| Azinphos-methyl (Guthion) | Insecticide |
| Chlorpyrifos (Lorsban) | Insecticide |
| Diazinon (several) | Insecticide |
| gamma-HCH (Lindane) | Insecticide |
| Parathion (several) | Insecticide |
| Yakima River Basin | |
| Metribuzin | Herbicide |
| Azinphos-methyl (Guthion) | Insecticide |
| Carbaryl | Insecticide |
| Diazinon (several) | Insecticide |
| Malathion | Insecticide |

In addition to filtering excess nutrients generated from agricultural practices, VFSs are also capable of filtering pesticides (Correll 1997). A recent literature review of VFSs and herbicide reduction found that nearly all of the literature indicated that VFSs can significantly reduce herbicide levels in runoff (Krutz et al. (2005). However, a majority of the experiments aimed at determining herbicide reduction were conducted at small scales and not at the scale of stream systems (Krutz et al. 2005).

On a larger scale, experiments designed to test the reduction of pesticides by buffers have primarily focused on the use of grasses. Using a grassy buffer between the field edge and stream margin, Antonious (1999) designed an experiment to test the removal of Dacthal from pepper and tomato crops in Kentucky. Results indicated that fescue buffers planted between each row of crops effectively removed 95% to 100% of Dacthal from runoff. To successfully implement VFSs as pesticide filters, the tolerance of the vegetation to herbicide application must be determined. Under controlled experimental conditions, Lin et al. (2004) tested the bioremediation capacity for six grass species exposed to the herbicides atrazine and isoxaflutole. The remediation potential among the grasses tested was highest for smooth bromegrass, tall fescue, and switchgrass (Lin et al. 2004). Comparing soil from a vegetative buffer strip with that from an adjacent area of bare land that had previously been used for the cultivation of cotton led researchers to conclude that higher organic carbon and elevated levels of microbial constituents readily retain and breakdown metolachlor in soils buffered with vegetation (Staddon et al. 2001).

The pesticide and herbicide removal potential of buffers has also been examined by testing different vegetative treatments either through combinations of herbaceous material or singly by comparing individual plant species. In the Midwest, sorghum pastures did not filter pesticides and herbicides as effectively as the grass or grass-wood-shrub buffers. There was no difference in contaminant filtering capabilities between the grass and grass-wood-shrub treatments (Schmitt et al. 1999). At slopes equal to 14%, buffers maintained at a constant width and comprising multiple species of grasses filtered runoff of glyphosate, propiconazole, and fenpropimorph at efficiencies of 39%, 63% and 71%, respectively (Syversen & Bechmann 2004).

A Mississippi field study examining the runoff concentrations of the herbicides fluometuron and norflurazon found the rate of reduction was dependant on both the type of grass and the rates of solubility and adsorption (Rankins et al. 2001). Of the four grasses examined, big bluestem, eastern gamagrass, switchgrass, and tall fescue, all significantly reduced fluometuron concentrations in runoff compared with no-grass treatments (Rankins et al. 2001). Although each of the studies outlined above have shown to some extent that grasses can be used for filtering and remediating pesticides, none have tested the variability of buffer width on removal efficiencies.

In the literature examined, studies to determine the removal potential of pesticides and herbicides used buffers ranging from 0 m to 18 m. Although these widths may or may not represent width increments of natural buffers, the variability in results may help determine whether width is an important factor with regard to contaminant filtration. Four pesticides, atrazine, isoproturon, diflufenican, and lindane, were applied to corn and wheat crops with the purpose of investigating the effectiveness of grassed buffers at variable widths (6 m, 12 m, and 18 m). Removal effectiveness for all four pesticides tested at the three widths ranged from 76% to 100% (Patty et al. 1997). Although the greater widths were more effective at removing pesticide residue, ultimately, all widths were effective at reducing concentrations under natural rainfall conditions.

Simulated runoff using multiple vegetative treatments at two width increments was applied to examine the filtration and removal potential of buffers in Nebraska. Increasing plot width from 7.5 m to 15 m increased the removal efficiencies for contaminants atrazine, alachlor, and permethrin (Schmitt et al. 1999). Both 4.6-m and 9.1-m grass-filter strips were used in a study by Mickelson et al. (2003), which determined that length played a significant role in the reduction of atrazine.

Modeling has become an increasingly common method for simulating the fate of pesticides while manipulating parameters such as buffer width and vegetation types. Researchers in Lin et al. (2002) applied information on topography and soil conditions to determine that buffer effectiveness is most related to buffer width, the type of vegetation used in the buffer, and the location of the buffer width. Another model designed to examine the risks imposed by pesticides to streams found buffers 10 m to 15 m wide were sufficient to reduce surface water runoff and contaminants (Probst et al. 2005). Runoff was greater for loamy soils than for sandy conditions; however, differences between soil types were negligible at buffer widths greater than 15 m (Probst et al. 2005).

A summary of studies addressing the efficiency of pesticide removal is presented in Table 4. Drawing from the literature reviewed, buffers maintain a certain degree of effectiveness to mitigate pesticides and herbicides from agricultural practices. Yet the literature only contains a sampling of the possible pesticides and herbicides currently applied to agricultural lands. Vegetation may reduce some pesticides and herbicides, but the transport of these chemical pollutants into waterways is also dependant on the characteristics of the chemical, as well as the soil and water properties of a given area (Antonious 1999). The solubility and the binding properties of the pesticides and herbicides themselves may ultimately determine the removal potential with riparian buffers or VFSs (Schmitt et al. 1999). Source-control measures, such as limiting application of pesticides and herbicides to specific areas or controlling the timing of application to minimize runoff potential, are often cited as possible methods, in addition to riparian buffers, for reducing the input of these chemicals into receiving waters (NRC 2002).
Again, the site-specific nature of riparian buffer effectiveness is important to emphasize.

**Table 4.** Summary of Reviewed Documents on Buffer Efficiency of Pesticide Removal

| Pesticide | Citation | Buffer type | Buffer Width | Region | Summary/efficiency | Comments | Pesticide Detected in the Interior Columbia Basin[(a,b)] |
|---|---|---|---|---|---|---|---|
| Alachlor | Schmitt et al. (1999) | mixed grasses<br>multi-species buffer (shrubs and trees) | 7.5 m<br>15 | Nebraska | Contaminant removal efficiency is positively correlated to buffer width | | X |
| Atrazine | Lin et al. (2004) | multiple grass types | NA | Missouri | Not all grasses tested were equally effective at atrazine removal | | X |
| | Mickelson et al. (2003) | VFS | 4.6 m<br>9.1 m | Iowa | 31.20%<br>79.10% | | |
| | Patty et al (1997) | mixed grasses | 6-18 m | France | 76%-100% | Wider widths were most effective at removal | |
| | Schultz et al. (1995) | multi-species buffer (grass, shrubs, trees) | 3.2-10 m | Iowa | The multi-species riparian buffer was effective at reducing atrazine in each of the three zones | | |
| | Schmitt et al. (1999) | mixed grasses<br>multi-species buffer (shrubs and trees) | 7.5 m<br>15 | Nebraska | Contaminant removal efficiency is positively correlated to buffer width | | |
| DCPA | Antonious (1999) | fescue strips | NA | Kentucky | 95%-100% | Fescue was interspersed between crop rows; not a stream-side buffer study. | X |
| Diflufenican | Patty et al. (1997) | mixed grasses | 6-18 m | France | 76%-100% | Wider widths were most effective at removal | |
| Fenproimorph | Syversen & Bechmann (2004) | mixed grasses | 5 m | Norway | 71% | Simulated runoff; 14% slope | |
| Fluometuron | Rankins et al. (2001) | multiple grass species | 30 cm | Mississippi | ≥59% for all grasses tested | Natural and simulated rainfall; 3% slope. | |

| Pesticide | Citation | Buffer type | Buffer Width | Region | Summary/efficiency | Comments | Pesticide Detected in the Interior Columbia Basin[(a,b)] |
|---|---|---|---|---|---|---|---|
| Glyphosate | Syversen & Bechmann (2004) | mixed grasses | 5m | Norway | 39% | Simulated runoff; 14% slope | |
| *alpha*-HCH (lindane) | Patty et al (1997) | mixed grasses | 6-18 m | France | 76%-100% | Wider widths were most effective at removal | X |
| *gamma*-HCH (lindane) | | | | | | | |
| Isoproturon | Patty et al. (1997) | mixed grasses | 6-18 m | France | 76%-100% | Wider widths were most effective at removal | |
| Metolachlor | Staddon et al. (2001) | mixed grasses | NA | Mississippi | Compared with bare plots, metolachlor was broken down more readily in vegetated plots. | This study was a soil analysis compared to others examining contaminants in runoff. | X |
| Norflurazon | Rankins et al. (2001) | multiple grass types | 30 cm | Mississippi | ≥46% for all grasses tested | | X |
| *cis*-Permethrin | Schmitt et al. (1999) | mixed grasses<br>multi-species buffer (shrubs and trees) | 7.5 m<br>15 | Nebraska | Contaminant removal efficiency is positively correlated to buffer width | | X |
| Propiconazole | Syversen & Bechmann (2004) | mixed grasses | 5 m | Norway | 63% | | |

[a] Williamson et al. 1998, Ebbert & Embrey 2002, Fuhrer et al. 2004, Orme & Kegley 2006
[b] For a complete list of pesticides detected in the interior Columbia River basin, refer to Appendix B.

## 11.0 Temperature Regulation and Microclimate

The majority of agro-riparian studies involving the manipulation of buffer width and vegetative composition have focused on the pollutant removal potential and water-quality benefits of buffers. These studies have improved our understanding of riparian processes in agricultural areas, yet there are still many questions to be addressed, especially in the area of habitat function of agricultural buffers. With most research focusing on water-quality aspects of buffers in agricultural areas, other riparian processes have not been thoroughly investigated. Until data gaps in the riparian-agriculture setting are researched, managers and policy makers must make inferences based on the current knowledge of riparian buffers in forested areas (Knutson & Naef 1997, May 2003, Naiman et al. 2005).

Shade is an important function of riparian vegetation in that it strongly influences the regulation of instream water temperature. Water temperature is one of the most crucial environmental factors influencing fish and other aquatic species. Essentially all biological processes in the life cycle of aquatic organisms are affected by water temperature. Daily and seasonal water temperatures are influenced by elevation, shade, water sources, streamflow, stream velocity, surface area, depth, undercut embankments, organic debris, and the inflow of surface water and groundwater (Naiman et al. 2005). Riparian vegetation moderates the amount of light reaching the stream channel by blocking or filtering solar radiation. The resulting shade helps to maintain cooler water temperatures. The effectiveness of riparian vegetation in producing shade depends on the composition, height, and density of riparian vegetation, and the width of the stream channel and its orientation relative to solar angle (FEMAT 1993, Gregory et al. 1991, Naiman et al. 1992, Kauffman et al. 1997, Palone & Todd 1997). Riparian vegetation is less effective in providing shade and moderating temperatures as streams increase in size. Its greatest impact is on headwater streams where it helps maintain the temperature of both the surface water and the shallow groundwater that feeds the stream. Although shading on larger rivers may have little or no influence on water temperature, overhanging riparian vegetation along the banks creates cooler micro-habitat for fish and aquatic organisms (Palone & Todd 1997). Figure 15 illustrates some of the relationships between riparian buffer width and associated functions, such as temperature regulation or shade.

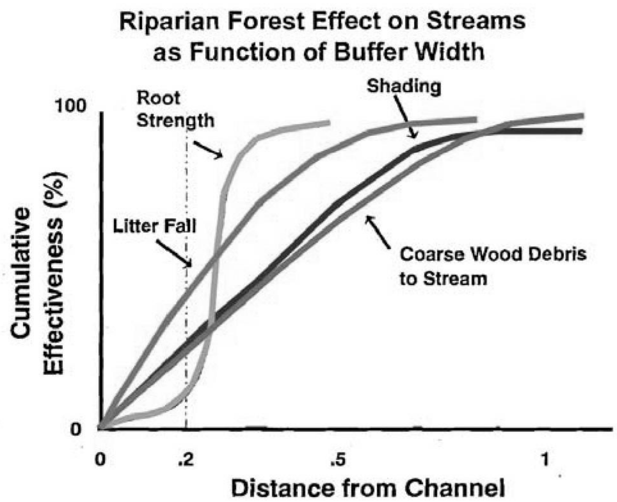


**Figure 15.** Cumulative effectiveness of riparian forest functions relative to the distance from the edge of the stream, expressed as fractions of site potential tree height (Modified from FEMAT 1993).

Riparian vegetation also exerts strong control on the stream microclimate by protecting it against climatic changes caused by land-use activities outside the riparian corridor. The microclimate of riparian corridors is uniquely different from upland areas because of its proximity to water, which moderates temperature and relative humidity. The microclimate of riparian areas is generally more moist and mild (i.e., cooler in summer and warmer in winter) than the surrounding area (Swanson et al. 1982, Naiman et al. 1992, Chen et al. 1995, Kauffman et al. 1997, Pollock & Kennard 1998, Naiman et al. 2000). This creates diverse habitat characteristics that are desirable to many species, particularly for amphibians year-round and for birds and mammals during hot, dry summers and severe winters (Knutson & Naef 1997).

The riparian corridor along streams also ensures adequate soil moisture available to riparian-associated plants throughout most of the year. Because of this microclimate, riparian vegetation is buffered from the stress of evapotranspiration during the summer (Swanson et al. 1982, Kauffman et al. 1997, Naiman et al. 2000). During winter months, riparian areas can be warmer than upland areas because they are not exposed to the winds more common in higher elevations (Swanson et al. 1982). Based on current research, the riparian forest is critical to the maintenance of local microclimate within the stream-riparian ecosystem. In addition, the riparian microclimate also influences water quality by helping regulate stream water temperature.

The previously cited USGS study of the interior Columbia River basin examined stream habitat conditions and found that streams in the study only contained an average of 20% canopy cover. Such reduced levels of canopy cover were correlated with increased instream temperatures and elevated levels of sediment loading (Williamson et al. 1998). Lack of historical riparian vegetation has likely influenced the degradation of these stream habitats. For example, stream temperatures in the Palouse region also exceeded thermal thresholds for aquatic organisms (Williamson et al. 1998). In Fuhrer et al. (2004), the lack of canopy cover in the Yakima basin was correlated with increased stream temperatures and elevated levels of algal biomass. The later condition was attributed to a combination of decreased riparian vegetation (e.g., lack of shade) and excessive levels of nutrient loading (Fuhrer et al. 2004).

The integrity of the riparian ecosystem can constrain the effectiveness of temperature regulation when riparian patchiness occurs in lieu of continuous corridors (Fischer & Fischenich 2000). Under some riparian design schemes, woody vegetation such as shrubs are acceptable as they afford substantial root structure for stabilization and provide cover for some wildlife; however, shrubs fall short of providing adequate shade to streams (Schultz et al. 2004). Stream order is an important consideration when determining buffer width. Due to their size, small order streams are closely linked to their riparian areas and may not require large buffers to regulate stream temperatures when compared with larger order streams (Palone & Todd 1997). In the interior Columbia River basin, the ecological interaction between stream and riparian areas may be more pronounced in headwater environments where riparian vegetation may be more influential at small streams (Quigley et al. 1997b).

## 12.0 Large Woody Debris and Organic Matter

Riparian vegetation adjacent to streams, lakes, and wetlands provides a significant portion of the organic material into aquatic food webs (Naiman et al. 2005). These allochthonous inputs are an important feature of stream-riparian ecosystems. The characteristics of the riparian plant community determine the quantity, quality, and timing of nutritional resources delivered to the aquatic ecosystem (Swanson et al.

1982, Gregory et al. 1991, Naiman & Decamps 1997). Leaves, fruit, cones, insects and other OM fall directly into the stream channel from the riparian area, or move by wind, erosion, or as dissolved materials in subsurface water flowing from the hyporheic zone (Gregory et al. 1991, Naiman et al. 1992, Naiman et al. 2000). Shrub and herb-dominated riparian communities such as those found in the interior Columbia River basin of eastern Washington and Oregon provide significant input to many streams (Gregory et al. 1991). CPOM is processed by macroinvertebrates that break down wood fragments, needles, leaves, and other debris into fine particulate organic matter (FPOM) that can then be processed by other organisms at the base of the aquatic food web. Figure 15 illustrates some of the relationships between riparian buffer width and associated functions, such as shade and streambank stability, as well as OM and LWD input for forested streams.

The input of OM from riparian buffers in agricultural areas has been addressed in only one study. An apparent link between buffer width and quantity of litterfall was discovered in a restored Ontario agricultural riparian area. Although the widest buffer yielded the largest litterfall in the restored riparian area, quantities were less than the amount of litterfall in a mature forest, which also bordered agricultural lands. Results from this study were unable to conclusively correlate buffer width to litterfall production in the streams, because two other treatments, a thinned buffer (10 m to 50 m) and a narrow buffer (2 m to 5 m) yielded little differences in litterfall.

LWD, such as branches, logs, uprooted trees, and root wads, are an important component of aquatic habitats in most forested stream-riparian ecosystems, both as a structural element and as cover for instream biota from predators or protection from high streamflows. LWD helps form channel features, such as pools, riffles, side channels, and meanders, and adds hydraulic complexity. Stream complexity is essential for many aquatic organisms, especially salmonid fish, because they require different types of habitat at various life stages. LWD also controls the routing of water and sediment, dissipates stream energy, protects streambanks, stabilizes streambeds, helps retain OM, and acts as a surface for biological activity. LWD enters streams either directly from the adjacent riparian area or from hill slopes through a variety of mechanisms, including toppling of dead trees, wind-throw, debris avalanches, undercutting of streambanks, and redistribution from upstream. Over time, the influence of LWD may change, both in terms of its function and location within the watershed, but its overall importance is significant and persistent. The characteristics of riparian vegetation determine the age, species, diversity, and size of the woody debris entering the stream, which in turn influences the persistence of LWD in the channel. (Swanson et al. 1982, Harmon et al. 1986, Bisson et al. 1987, Bilby & Ward 1989, Gregory et al. 1991, Naiman et al. 1992, FEMAT 1993 , Naiman et al. 2005)

In contrast to the body of literature cited above, this review of agricultural buffer studies applicable to the interior Columbia River Basin has not encountered any studies generating empirical data related to the association of LWD with agricultural riparian areas. A study of LWD and riparian zones in areas of eastern Washington was recently completed, although the primary focus of this review centered on forested regions (Herrera 2004).

## 13.0 Instream Habitat

In general, natural riparian areas are biologically diverse and complex ecosystems that contain more plant, mammal, bird, and amphibian species than the surrounding upland areas. Wildlife use riparian corridors more than any other type of habitat (Knutson & Naef 1997). Riparian areas provide several functions important to wildlife, including the following:

- Food and Water
- Protective Cover
- Breeding and Nursery Areas
- Migration Corridor
- Microclimate.

The ability of the riparian corridor to attract and support fish and wildlife is dependent on the structural and functional integrity of the aquatic, riparian, and upland ecosystems (Knutson & Naef 1997). The influence riparian areas exert on a stream is related to the size of the stream, its location in the watershed, the hydrologic pattern, and local landforms (Naiman et al. 1992). Wildlife tends to be attracted to riparian areas because of the abundance of food sources, cover, and proximity of drinking water. Access to water is critical for both riparian-dependent wildlife and for many upland species, especially in urban areas where access can be a limiting factor

Many wildlife populations rely on their ability to move between different types of habitat along riparian corridors, especially species that would not otherwise move across large open spaces (Palone & Todd 1997). Riparian corridors, because of their linear shape, enable movement of wildlife between habitat patches. Dispersal and establishment of new territories for feeding and breeding is important for many species, allows for an exchange of genetic material between populations, and is critical for resilience to disease and other negative impacts (Palone & Todd 1997). Riparian corridors also play a potentially important role within landscapes as corridors for plant dispersal and, according to Gregory et al. (1991), may be an important source of most colonists through the landscape.

Historically, animals have been viewed as passive components of riparian ecosystems, merely responding to the local conditions. In many cases, however, animals are responsible for biogeochemical, successional, and landscape alterations that may persist for centuries (Naiman et al. 2000). For example, in riparian zones, the numbers of animals and the abundance and quality of food vary constantly but irregularly in time and space. These variations are connected with variations in abundance of some animals and have indirect effects on the abundance of others, thereby affecting system-level characteristics. For example, selective foraging by some large mammals such as beaver can change plant species composition, nutrient cycling rates, and soil fertility (Naiman et al. 2000). Beaver have been shown to be an important biological component of streams in the interior Columbia River basin of eastern Washington (Pollock et al. 2004). Selective browsing by deer and elk on hardwood species (e.g., willow and alder) and certain conifers (e.g., cedar and fir) allows less-browsed conifers (e.g., spruce and hemlock) to dominate the riparian landscape (Schreiner et al. 1996).

Although no specific research has been conducted on the habitat functions of agricultural riparian buffers in the interior Columbia River basin, the value of these areas to wildlife is likely comparable to other regions where extensive research has been conducted (Knutson & Naef 1997).

# 14.0 Synthesis

Impacts of human activities on stream-riparian ecosystems are numerous and highly variable. The effects of land-use activities are often due to multiple stressors and are usually cumulative in their impact. The characteristics of the stream-riparian ecosystem will also influence the extent and intensity of the human-induced disturbance. Site-specific variables such as stream size, location within the watershed, stream gradient, valley configuration, valley side-slope, watershed topography, soil type, riparian vegetation conditions, rainfall patterns, and others all combine to make some stream-riparian ecosystems more or less sensitive to human land-use impacts (Knutson & Naef 1997).

Agricultural activities such as farming and livestock grazing can adversely impact stream-riparian ecosystems (NRC 2002). The quality of agricultural runoff can significantly affect stream water quality. Agricultural crop production can be a significant source of pollution, including fine sediment from exposed soil, nutrients from fertilizers, and toxic pollutants from pesticides and herbicides. Improper grazing practices can also degrade the stream-riparian ecosystem in other ways, including loss of riparian vegetation due to grazing, erosion of streambanks due to livestock access, increased turbidity from fine sediment inputs, and bacterial pollution from livestock waste. In general, research has indicated that use of proper agricultural BMP, limiting livestock access to the stream and riparian area using fencing, and maintenance of vegetative buffers along the riparian corridor can significantly reduce the impacts of agricultural activities (Lowrance et al. 1984, Dillaha et al. 1989, Meehan 1991, Lowrance et al. 1997, NRC 2002).

Although many local, state, and federal agencies have begun to focus efforts aimed at restoring and enhancing riparian areas disturbed by land-use activities, the goals associated with these programs can differ widely between jurisdictions (e.g., CREP). A typical approach focuses on restoring multiple ecosystem functions and processes, whereas a mitigation-based approach may implement measures to enhance riparian functions, which are designed to alleviate adverse impacts resulting from adjacent land-use activities.

Management of riparian zones requires specific knowledge of multiple factors, including hydrologic, soil, and vegetative conditions, as well as potential sources and types of pollution. This knowledge must be broken down into specific reaches within a watershed, as site variation can yield different outcomes for riparian function. The appropriate buffer size will depend on the spatial area necessary to maintain the desired riparian functions and on the combination of land-use activities that are influencing the stream-riparian ecosystem. For example, a wider buffer may be required in areas of high-intensity land-use than in areas of low-intensity land-use. Similarly, all else being equal, a sensitive stream used extensively by aquatic biota and wildlife may require a larger buffer than would a stream used only as a migration corridor for fish.

Of equal importance to buffer size (i.e., width and extent of the corridor) is the quality of the riparian area in terms of vegetation type, diversity, physical condition, and maturity. Ideally, a riparian corridor in an agricultural area should mirror that found in the natural ecosystems of that region. Due to the cumulative impacts of past and present land use, this is often not the case. Many streams have narrow, fragmented riparian corridors that lack the mature coniferous trees, which characterize the few, pristine watersheds that remain. In general, the relatively young, riparian forests that are common in many watersheds do not provide all of the functions that mature riparian forests support. The supply of allochthonous OM and LWD provided to the stream, the rain interception capacity of the canopy, and the shade are different from that supplied by natural riparian forests. In addition, exotic and invasive vegetation is typically more common in impacted riparian corridors than in wide, natural corridors. In general, native vegetation is preferred over exotic or landscaped plantings for riparian buffers. The exception to this is the use of VFSs, usually grasses used specifically to treat stormwater or agricultural runoff. In short, the quality of riparian buffers should closely mimic if not equal that of natural ecosystems.

In addition, natural riparian corridors are generally nearly continuous throughout the stream-riparian ecosystem (NRC 2002). In addition to buffer width and quality, management of the riparian corridor should also focus on minimizing fragmentation (Figure 16). Road crossings, utility right-of-ways, and other breaks in the riparian corridor effectively reduce the buffer width to zero and provide a conduit for runoff and pollutants to enter the stream (NRC 2002). Breaks in the riparian corridor should be kept to a minimum so as to reduce corridor fragmentation.

As has been emphasized throughout this report, the effectiveness of buffers is dependant on site-specific factors, including slope and soil condition, vegetation type, buffer zone density, buffer size, and degree of connectivity. Effectiveness is often assessed based on specific management goals. In agricultural areas, managers are most often concerned with pollutants and water-quality impacts. Hence, nationwide, agricultural research has focused on these buffers attributes. The research reviewed in this report indicates that riparian buffer revegetation through various planting schemes can mitigate for some water-quality impacts caused by agricultural practices (USDA 2000, Lowrance et al. 1997, Schultz et al. 2004). It is also evident from the literature that agricultural buffer design should include site-specific information related to soil and slope condition, as well as knowledge of the upland contributing areas (Lowrance et al. 1997, Dosskey et al. 2005).

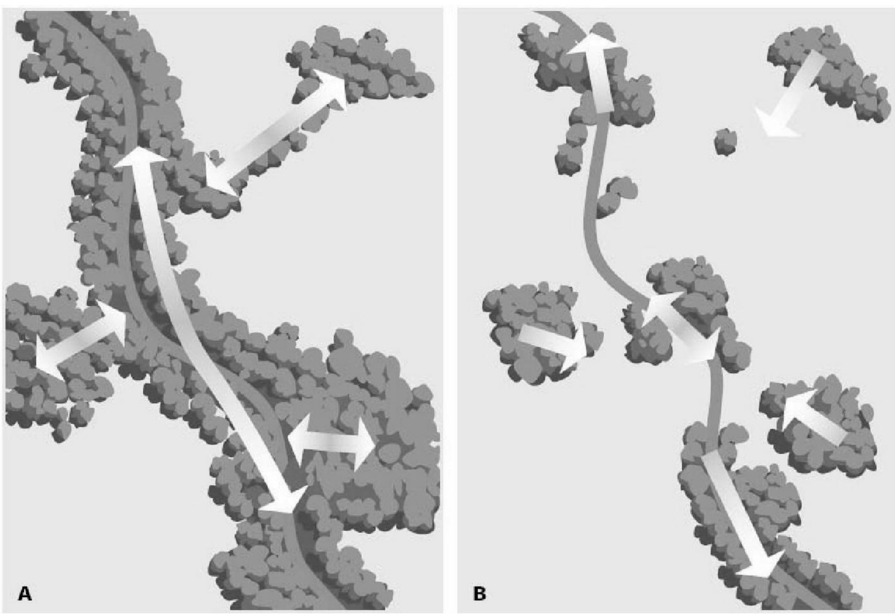


**Figure 16.** Riparian corridor fragmentation: A) high connectivity with low fragmentation, and B) highly fragmented with little riparian connectivity (FISRWG 1998).

Requirements for standard buffer widths along stream margins may prove to be ineffective if buffers are too narrow; standard widths could also create operational or economic constraints to farmers if buffer requirements are wider than necessary based on functional requirements. Some research supports buffer design that accounts for unevenness in surface runoff patterns by implementing variable width buffers along a stream gradient. Depending on site characteristics, larger widths are placed at stream segments receiving the bulk of runoff material, whereas smaller buffers are effectively used in less high-risk areas (Dosskey et al. 2005). In some cases, buffer regulations and design approaches aimed at maximizing stream conservation may not be readily embraced by landowners. Issues identified by the Washington CREP program support this rationale (Smith 2006).

The findings of the research reviewed for our report generally indicate that buffer width should be established based on the surrounding environmental conditions. Narrower buffers are more acceptable if the system is already in a natural state or when upland activities impose low impacts to the stream-riparian ecosystem. Larger buffers are often necessary when land-use impacts pose an eminent threat to the stream and when existing riparian zones are ecologically inadequate for providing appropriate functions (Castelle et al. 1994, Palone & Todd 1997, May 2003). Furthermore, smaller buffers may be adequate for protecting water quality of streams, but larger buffers are often needed to provide habitat-related functions benefiting aquatic organisms and terrestrial wildlife (Castelle et al. 1994). Other considerations include slope and stream order. Greater buffer widths may be required at sites surrounded by steep topography. The potential for pollution input also tends to increase with the size of the contributing area (Palone & Todd 1997).

Currently, principles that shape buffer placement, width, and vegetative composition in agricultural areas are primarily based on standards for protecting water quality of streams (Fischer & Fischenich 2000). This focus often leads to an approach that emphasizes the use of VFSs as the primary riparian buffer mechanism. In most cases VFS buffer placement is designed to follow land contours adjacent to agricultural areas. Widths of buffers that are implemented with the sole intent of filtering pollutants can vary depending on management goals. It is not always appropriate to assume a linear relationship between buffer width and efficacy for pollutant removal (Palone & Todd 1997). Nutrient filtration requires larger buffer widths than do buffers designed for sediment retention (USDA 2000).

The USDA riparian-forest buffer system adopts principles of the classic three-zoned buffer to represent a management approach that has been designed with ecosystem sustainability in mind (Lowrance et al. 1997). As with VFSs, slope can be a factor limiting the effectiveness of forested buffers. However, the overall longevity of forested buffers are considered superior to alternative management practices such as VFSs (Lowrance et al. 1997). In the Midwest, the riparian management system model (RiMS) has been applied to agricultural areas. Although the planting scheme of RiMS slightly differs from the three-zone model, the primary goals are similar. Through minimizing the effects of agriculture, RiMS seeks to restore the biological and hydrological mechanisms of riparian ecosystems (Simpkins et al. 2005).

To some land owners, however, large trees along streams are undesirable as they can create drainage and flow problems that can negatively affect farming practices. With this in mind, a two-zone buffer system was developed to eliminate large wood in streams (Schultz et al. 2004). The composition of the two-zone multi-species buffer is quite similar to the three-zone riparian buffer, except that large woody vegetation near the stream bank is not left unmanaged as in the three-zone system. In another approach to buffer design, Schultz et al. (2004) offer a scheme similar to the three-zone system, but with the flexibility to implement different vegetation types and widths for the benefit of the land-owner.

In general, buffers that mimic natural vegetative conditions offer the best choice, because these provide function and habitat in riparian zones (Palone & Todd 1997). A multitude of vegetative combinations can be used for riparian plantings, including grasses, shrubs, and trees. In Palone & Todd (1997), forests were found to provide the greatest combination of ecosystem functions in riparian areas. Ultimately, conservation and restoration goals will determine the type of vegetation found within agricultural buffers.

Research has established that VFSs are effective at filtering pollutants in agricultural areas. However, the results of research efforts may be slightly misleading, as many studies are conducted at small scales. A frequently cited study, Dillaha et al. (1989), demonstrated that both 4.6-m and 9.1-m VFSs effectively reduced sediment and nutrient delivery from agricultural runoff. However, the contributing area of these research plots was only about one fifth as large as typical agricultural areas (Dillaha et al. 1989). Though effective in some respects, VFSs should not be used as the sole mechanism for riparian vegetation in agricultural areas and, in most cases, should be combined with native vegetation to support other riparian functions in addition to pollutant filtering (Dillaha & Inamdar 1997). Recommendations in Fischer and Fischenich (2000) state that to achieve a minimum of the array of multiple functions, buffers should be at least 10 m wide. In Gilliam et al. (1997), it is asserted that narrow buffers can be applied to mitigate water-quality impacts, yet buffers at least 29 m wide should be implemented to achieve multiple management goals.

In addition to multi-species riparian buffers and VFSs, grassy waterways, vegetated ditches, or biofiltration swales can be constructed to filter runoff from agricultural fields. These differ from VFSs in that swales are constructed as longitudinal pathways to treat runoff prior to it entering receiving waters (Fiener & Auerswald 2006). Although certain grasses have been demonstrated to effectively reduce runoff and filter pollutants, grasses alone will not provide sufficient wildlife habitat in riparian areas (Schultz et al. 2004).

Experiments designed to test the effectiveness of single-species versus multi-species plantings have produced results that support each management scheme. In central Iowa, restoration of riparian buffers along a stream running through an area dominated by row crops filtered nitrogen and atrazine from adjacent fields (Schultz et al. 1995). Four years following the implementation of the project, the effectiveness of the site was evaluated by comparing the functions of the three zone multi-species riparian buffer with those at control sites planted with pasture grasses. When compared with the control treatment, the superior filtering effectiveness of the multi-species buffer was attributed to a more well-developed and deeper root structure (Schultz et al. 1995).

Our review of agricultural buffers has answered many questions and helped to close the gap with regard to our present understanding of these systems. Much work has been conducted in the central and eastern portions of the United States where agriculture is a dominant form of land-use. Data specific to the arid and semi-arid regions of the western United States are sparse. Despite the prevalence of agriculture in eastern Washington and Oregon, few studies investigating the connectivity between agriculture and riparian corridors have been conducted.

An earlier literature review (Pizzimenti 2002) focused on agricultural buffers with special consideration to appropriate widths for Eastern Washington. This review concluded that agricultural buffers between 5 m and 30 m are able to provide the necessary functions related to filtration, shade, and bank stabilization. As is the case with other reviews of riparian buffer research, it is not uncommon to encounter a large variation in suggested ranges of "effective" buffer widths. However, our review of the Pizzimenti (2002) report indicated that the ranges of recommended buffer widths to support specific riparian functions are sometimes not supported by the literature cited. For example, the Pizzimenti study states that 10 m to 30 m of riparian vegetation is sufficient for shade regulation; however, no discussion regarding the specific sources used to draw this recommendation was provided. It appears that much of the data used originated from studies of riparian forests located in mountain regions. Regarding the relationship between riparian zones and LWD, Pizzimenti (2002) asserts buffer-width recommendations for forested streams may be exaggerated, but no justification for this conclusion is given. As was discussed earlier in this report, the specific role of LWD in lowland agricultural streams has yet to be determined (Quigley et al. 1997b).

# 15.0 Conclusions

Only a few studies have specifically focused on the effectiveness of riparian buffers in agricultural areas in the interior Columbia River basin. Despite this lack of research specific to the study area, a significant body of scientific literature exists from throughout the world that addresses the utility of using riparian management zones and buffers to protect receiving waters in areas dominated by agricultural land-use activities. This report summarizes the findings of those studies applicable to the interior Columbia River basin region. Based on BAS, it is evident that riparian buffers can significantly reduce the impacts of agricultural land-use activities on streams, lakes, and wetlands. Efforts to apply the current literature to management of agricultural areas are limited by the narrow scope of existing research. For the most part, agro-riparian studies have concentrated on the water-quality benefits of buffers in agricultural settings rather than on habitat functions or other ecological benefits. Appendix D summarizes the scientific literature used in this report.

A comparison of the extremes in riparian conditions (natural vegetation versus no buffer) found within riparian zones of the interior Columbia River basin where agriculture is the dominant land-use activity is useful in illustrating the effectiveness of riparian buffers. Natural riparian zones in this region are composed of a diverse mixture of trees, shrubs, grasses, and other vascular plants. The types of plants present in a given area depend on a variety of environmental conditions. The elevation, climate (e.g., rainfall patterns and temperature), soil type, and hydro-geomorphology all influence the suite of native vegetation present within the riparian zone (Crawford 2003). The native vegetation found in riparian corridors along streams in the interior Columbia River basin will typically change over a gradient of elevation, climate, and soil (Wissmar 2004). In addition, the presence of beaver and other biota can also influence the type and diversity of riparian vegetation (Pollock et al. 2004).

As is the case with vegetation type, the extent or width of riparian areas can also be quite variable under natural conditions. In semi-arid regions such as the interior Columbia River basin, the hydro-geomorphic characteristics, such as surface and groundwater interactions, soil type, and topography of the stream channel will largely determine the lateral extent (i.e., width) of the riparian corridor. The presence of hydric soils, the level of the groundwater table, and the presence of surface seeps will influence where riparian vegetation is found. In addition, streams located in ravines or constrained valley-bottoms will have a narrower riparian corridor than will streams associated with floodplain areas or where riparian wetland complexes exist. In general, incised channels tend to have narrower riparian corridors than do non-incised channels.

Natural, unimpacted riparian zones typically support a full suite of riparian functions. These include temperature regulation (e.g., shading), sediment filtration, nutrient processing, streambank stabilization, and enhanced habitat features, as well as pollutant filtration and capture.

In contrast to natural riparian conditions, the "no-buffer" condition, which is common in agricultural areas in the interior Columbia River basin, has significantly different riparian characteristics. Typically, little to no native vegetation exists, and what little there is tends to be highly fragmented and degraded by land-use encroachment. Row-crop agriculture can often be found directly adjacent to streams. Non-native or invasive plants are also common. Grazing pressure often results in extensive streambank destabilization, erosion, and sedimentation of receiving waters. Channel incision is also common in streams that have a history of agricultural activity, water withdrawal, and/or human development in their contributing watersheds. In some cases, the only buffer present is in the form of a VFS.

In general, the "no-buffer" condition provides little functional value to the associated aquatic ecosystem. Temperature regulation (e.g., shading), sediment filtration, nutrient processing, streambank stabilization, and habitat features, as well as pollutant filtration and capture are all minimal or nonexistent without a natural riparian area adjacent to a water body. If a VFS or grassy buffer is provided, typically only the water-quality functions (i.e., nutrient, sediment, and pollutant filtering) are provided, depending on the width of the VFS and the characteristics of the vegetation-soil complex. Grassy buffers or VFSs can also provide some measure of streambank protection from erosion. However, these types of buffers appear to have little or no habitat value compared with natural riparian areas.

Our review reveals that many of the functional responses of riparian ecosystems in agricultural landscapes have not been fully researched to the point where the range of functional effectiveness can be defined without some uncertainty (Figure 17). The efficacy of pollutant filtration within agro-riparian studies has been derived under experimentally manipulated conditions as well as in situ-based studies. Due to the large variability among riparian widths, an ecosystem-based management approach will offer the most practical option for protecting streams and their biotic constituents. Furthermore, compared with single species buffers (e.g., grass and forest), stream-side vegetation comprised of multiple vegetation types (e.g., a combination of grasses, shrubs, and trees) has been found to increase the efficacy pollutant filtration.

Compared with empirically derived agro-riparian studies, the minimum buffer width (e.g. 35 feet) required by Washington CREP likely provides protection to streamside ecosystems through sediment, nutrient, and pesticide filtration. To our knowledge buffer widths within agricultural landscapes have not been empirically evaluated with regard to providing fish and wildlife habitat, LWD inputs, and temperature regulation to nearby streams. Using data from forested riparian studies as a template for agro-riparian ecosystems indicates a 35 foot buffer may not be effective at regulating all streamside ecosystem processes.

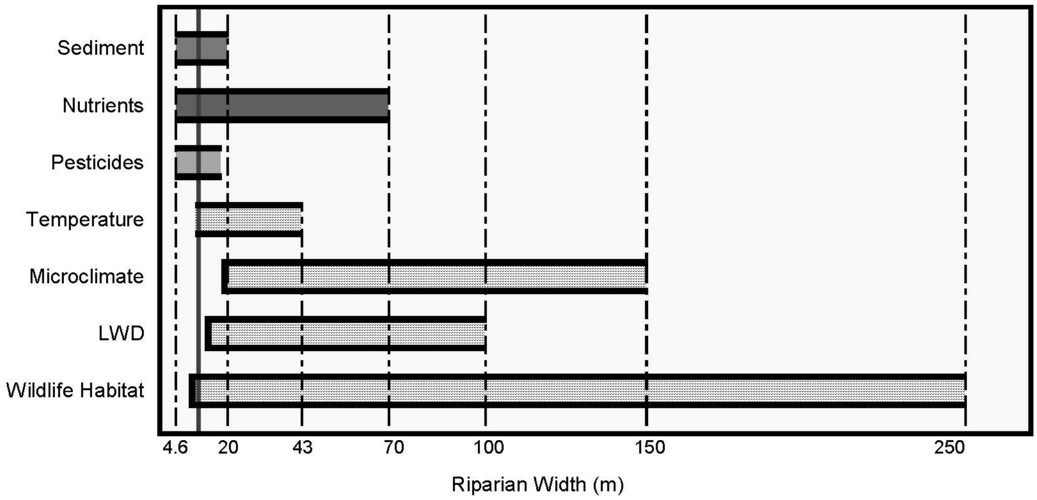


**Figure 17.** Summary of riparian response variables related to buffer width. Solid bars represent buffer widths derived from experimental and in situ studies specifically targeting agricultural landscapes. Horizontally shaded bars correspond to response variables and buffer widths obtained from literature sources in which the scope of research did not include agricultural landscapes (May 2003). Response variables characterized by the horizontally shaded bars should be considered as data gaps with regard to the function of riparian ecosystems in agricultural settings. The solid red line depicts the minimum Washington state CREP buffer width.

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# Appendix A

## Columbia Basin Riparian Vegetation and Select Functions (table adapted from Crawford 2003).

**Key:**

OW = obligate wetland species; always occurs in wetlands
FW = faculatative wetland species; occurs in wetlands 67-99% of the time
F = faculatative species; occurs in wetlands or uplands
FU = faculatative upland species; occurs in wetlands 1-33% of the time
U = obligate uplands species; always in uplands
- = undetermined

H = high potential
M = medium
L = Low

G = good
F = fair
P = poor

| Wetland Status | Native Status | Common Name | Scientific Name | Erosion Control | Short-term revegetation | Long-term revegetation | Wildlife Habitat |
|---|---|---|---|---|---|---|---|
| **Trees** | | | | | | | |
| F | native | bigleaf maple | Acer macrophyllum | - | - | - | - |
| F | native | black cottonwood | Populus balsamorhiza ssp. trichocarpa | H | L | M | F |
| F | native | black hawthorn | Crataegus douglasii | M | L | M | F |
| - | introduced | black walnut | Juglans nigra | - | - | - | - |
| FW | introduced | boxelder | Acer negundo | M | L | L | G |
| FU | native | common chokecherry | Prunus virginiana | M | L | H | G |
| - | native | greenleaf willow | Salix lucida ssp. caudata | - | - | - | - |
| F | introduced | honey locust | Gleditsia triacanthos | - | - | - | - |
| F | native | netleaf hackberry | Celtis laevigata var. reticulata | - | - | - | - |
| FU | native | Oregon white oak | Quercus garryana | - | - | - | - |
| FW | native | peachleaf willow | Salix amygdaloides | H | L | M | G |
| FU | native | ponderosa pine | Pinus ponderosa | - | - | - | - |
| FW | native | quaking aspen | Populus tremuloides | H | L | H | G |
| FU | native | Rocky Mountain juniper | Juniperus scopulorum | - | - | - | - |
| F | introduced | Russian olive | Elaeagnus angustifolia | - | - | - | - |
| FW | native | thinleaf alder | Alnus incana ssp. tenuifolia | - | - | - | - |
| FW | native | water birch | Betula occidentalis | H | L | M | G |
| FU | native | western juniper | Juniperus occidentalis | - | - | - | - |

**Key:**

| | | |
|---|---|---|
| OW = obligate wetland species; always occurs in wetlands | H = high potential | G = good |
| FW = faculatative wetland species; occurs in wetlands 67-99% of the time | M = medium | F = fair |
| F = faculatative species; occurs in wetlands or uplands | L = Low | P = poor |
| FU = faculatative upland species; occurs in wetlands 1-33% of the time | | |
| U = obligate uplands species; always in uplands | | |
| - = undetermined | | |

| Wetland Status | Native Status | Common Name | Scientific Name | Erosion Control | Short-term revegetation | Long-term revegetation | Wildlife Habitat |
|---|---|---|---|---|---|---|---|
| **Trees** | | | | | | | |
| FW | native | white alder | Alnus rhombifolia | - | - | - | - |
| FW | introduced | white willow | Salix alba | H | L | M | - |
| **Shrubs** | | | | | | | |
| FW | native | arroyo willow | Salix lasiolepis | - | - | - | - |
| FU | native | basin big sagebrush | Artemisia tridentata ssp. tridentata | L | L | L | L |
| FW | native | Bebb willow | Salix bebbiana | H | L | M | G |
| F | native | blue elderberry | Sambucus nigra ssp. cerulea | - | - | - | - |
| - | native | California blackberry | Rubus ursinus | - | - | - | - |
| FU | native | common snowberry | Symphoricarpos albus | M | L | M | G |
| - | introduced | dog rose | Rosa canina | - | - | - | - |
| F | native | golden currant | Ribes aureum | - | - | - | - |
| FU | native | greasewood | Sarcobatus vermiculatus | - | - | - | - |
| FU | native | heath goldenrod | Ericameria nauseosa ssp.nauseosa var. nauseosa | - | - | - | - |
| - | introduced | indigobush | Amorpha fruticosa | - | - | - | - |
| F | native | Lewis' mockorange | Philadelphus lewisii | - | - | - | - |
| FW | native | white sagebrush | Artemisia ludoviciana | - | - | - | - |
| FU | native | Nootka rose | Rosa nutkana | - | - | - | - |

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|---|---|---|---|---|---|---|---|
| **Shrubs** | | | | | | | |
| - | native | mallowleaf ninebark | Physocarpus malvaceous | - | - | - | - |
| - | native | oceanspray | Holodiscus discolor | - | - | - | - |
| FU | native | parsnipflower buckwheat | Eriogonum heracleoides | - | - | - | - |
| - | native | Pursh's buckthorn | Frangula purshiana | - | - | - | - |
| FW | native | redosier dogwood | Cornus sericea | H | L | M | F |
| OW | native | sandbar willow | Salix exigua | H | L | M | G |
| FU | native | Saskatoon serviceberry | Amelanchier alnifolia | M | L | M | F |
| F | native | Scouler's willow | Salix scouleriana | - | - | - | - |
| FU | native | smooth sumac | Rhus glabra | - | - | - | - |
| FU | native | snow buckwheat | Eriogonum niveum | - | - | - | - |
| FU | native | thimbleberry | Rubus parviflorus | - | - | - | - |
| - | native | wax current | Ribes cereum var. cereum | - | - | - | - |
| F | native | wedgeleaf saltbrush | Atriplex truncata | - | - | - | - |
| FW | native | western poison ivy | Toxicodendron rydbergii | - | - | - | - |
| FU | native | western white clematis | Clematis ligusticifolia | M | L | L | |
| - | native | white spirea | Spiraea betulifolia | - | - | - | - |
| F | native | whitestem gooseberry | Ribes inerme | - | - | - | - |
| FU | native | Woods' rose | Rosa woodsii | H | L | M | G |

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| Wetland Status | Native Status | Common Name | Scientific Name | Erosion Control | Short-term revegetation | Long-term revegetation | Wildlife Habitat |
|---|---|---|---|---|---|---|---|
| **Shrubs** | | | | | | | |
| FU | native | Wyoming big sagebrush | Artemisia tridentata ssp. wyomingensis | - | - | - | - |
| OW | native | yellow willow | Salix lutea | H | L | M | G |
| **Grass-Likes** | | | | | | | |
| OW | native | analogue sedge | Carex simulata | - | - | - | - |
| OW | native | Baltic rush | Juncus balticus | M | L | M | - |
| OW | native | chairmaker's bulrush | Schoenoplectus americanus | - | - | - | - |
| FW | native | clustered field sedge | Carex praegracilis | - | - | - | - |
| OW | native | common spikerush | Eleocharis palustris | H | H | M | - |
| OW | native | fewflower sedge | Carex pauciflora | - | - | - | - |
| OW | native | hardstem bulrush | Schoenoplectus acutus | M | M | M | G |
| OW | native | Nebraska sedge | Carex nebrascensis | - | - | - | - |
| OW | native | Northwest Territory sedge | Carex utriculata | H | M | H | P |
| OW | native | owlfruit sedge | Carex stipita | - | - | - | - |
| OW | native | panicled bulrush | Scirpus microcarpus | - | - | - | - |
| F | native | poverty rush | Juncus tenuis | - | - | - | - |
| OW | native | river bulrush | Schoenoplectus fluviatilis | - | - | - | - |

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| Wetland Status | Native Status | Common Name | Scientific Name | Erosion Control | Short-term revegetation | Long-term revegetation | Wildlife Habitat |
|---|---|---|---|---|---|---|---|
| **Grass-Likes** | | | | | | | |
| FW | native | slenderbeak sedge | Carex athrostachya | - | - | - | - |
| FW | native | swordleaf rush | Juncus ensifolius | - | - | - | - |
| OW | native | tapertip rush | Juncus acuminatus | - | - | - | - |
| FW | native | toad rush | Juncus bufonius | - | - | - | - |
| OW | native | water sedge | Carex aquatilis | H | M | M | - |
| OW | native | woolly sedge | Carex pellita | H | M | M | - |
| **Grasses** | | | | | | | |
| FU | native | alkali bluegrass | Poa secunda | - | - | - | - |
| FW | native | alkali cordgrass | Spartina gracilis | H | M | H | G |
| FW | native | annual hairgrass | Deschampsia danthonioides | - | - | - | - |
| FW | introduced | annual rabbitsfoot grass | Polypogon monspeliensis | - | - | - | - |
| FU | native | basin wildrye | Leymus cinereus | H | M | H | - |
| - | both | bentgrass | Agrostis spp | - | - | - | - |
| FU | native | blue wildrye | Elymus glaucus | M | M | H | - |
| U | native | bluebunch wheatgrass | Pseudoroegneria spicata | - | - | - | - |
| - | native | bluegrass | Poa species | - | - | - | - |
| FW | native | bluejoint | Calamagrostis canadensis | H | L | H | - |
| FU | introduced | bulbous bluegrass | Poa bulbosa | - | - | - | - |

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| Wetland Status | Native Status | Common Name | Scientific Name | Erosion Control | Short-term revegetation | Long-term revegetation | Wildlife Habitat |
|---|---|---|---|---|---|---|---|
| **Grasses** | | | | | | | |
| F | introduced | Canada bluegrass | Poa compressa | - | - | - | - |
| FU | introduced | cheatgrass | Bromus tectorum | - | - | - | - |
| F | introduced | colonial bentgrass | Agrostis capillaris | - | - | - | - |
| FW | native | creeping bentgrass | Agrostis stolonifera | H | H | H | - |
| F+ | introduced | Darbyshire meadow ryegrass | Lolium pratense | - | - | - | - |
| F | introduced | dense silkybent | Agrostis interrupta | - | - | - | - |
| OW | native | fowl mannagrass | Glyceria striata | M | L | M | - |
| F | native | foxtail barley | Hordeum jubatum | L | M | L | - |
| U | native | Idaho fescue | Festuca idahoensis | M | L | M | - |
| FW | introduced | intermediate wheatgrass | Elytrigia intermedia | - | - | - | - |
| U | introduced | Japanese brome | Bromus japonicus | - | - | - | - |
| FU | introduced? | Kentucky bluegrass | Poa pratensis | L | M | H | G |
| F | native | Lemmon's alkaligrass | Puccinellia lemmonii | - | - | - | - |
| FW | introduced | leporinum barley | Hordeum murinum ssp. leporinum | - | - | - | - |
| FW | native | mat muhly | Muhlenbergia richardsonis | - | - | - | - |
| FW | native | meadow barley | Hordeum brachyantherum | - | - | - | - |
| FU | introduced | medusahead | Taeniatherum caput-medusae | - | - | - | - |

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| Wetland Status | Native Status | Common Name | Scientific Name | Erosion Control | Short-term revegetation | Long-term revegetation | Wildlife Habitat |
|---|---|---|---|---|---|---|---|
| **Grasses** | | | | | | | |
| FU | native | Nevada bluegrass | Poa secunda | - | - | - | - |
| FU | introduced | orchardgrass | Dactylis glomerata | - | - | - | - |
| FU | introduced | quackgrass | Elytrigia repens var. repens | H | M | H | G |
| FW | introduced | reed canarygrass | Phalaris arundinacea | H | M | H | |
| U | introduced | rye brome | Bromus secalinus | - | - | - | - |
| FU | introduced | ryegrass | Lolium arundinaceum | - | - | - | - |
| FW | native | saltgrass | Distichlis spicata | M | L | M | P |
| U | native | Sandberg bluegrass | Poa secunda | - | - | - | - |
| - | both | six-week fescues | Vulpia spp. | - | - | - | - |
| FU | native | streambank wheatgrass | Elymus lanceolatus | - | - | - | - |
| FU | introduced | timothy | Phleum pratense | M | M | H | G |
| U | introduced | ventenatagrass | Ventenata dubia | - | - | - | - |
| OW | native | weeping alkaligrass | Puccinellia distans | - | - | - | - |
| **Forbes** | | | | | | | |
| - | introduced | absinthium | Artemisia absinthium | - | - | - | - |
| - | introduced | alfalfa | Medicago sativa | - | - | - | - |
| OW | native | alkali buttercup | Ranunculus cymbalaria | - | - | - | - |
| OW | native | American speedwell | Veronica americana | - | - | - | - |

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| Wetland Status | Native Status | Common Name | Scientific Name | Erosion Control | Short-term revegetation | Long-term revegetation | Wildlife Habitat |
|---|---|---|---|---|---|---|---|
| **Forbes** | | | | | | | |
| - | native | arrowleaf balsamroot | Balsamorhiza sagittata | - | - | - | - |
| OW | native | arumleaf arrowhead | Sagittaria cuneata | - | - | - | - |
| - | native | aster | Aster sp. | - | - | - | - |
| FU | native | bigbract verbena | Verbena bracteosa | - | - | - | - |
| F | introduced | black medick | Medicago lupulina | - | - | - | - |
| - | native | blue-eyed Mary | Collinsia grandiflora | - | - | - | - |
| F | native | blue lettuce | Lactuca tatarica var. pulchella | - | - | - | - |
| OW | native | broadfruit burreed | Sparganium eurycarpum | - | - | - | - |
| OW | native | broadleaf cattail | Typha latifolia | H | L | H | G |
| F | introduced | Perennial pepperweed | Lepidium latifolium | - | - | - | - |
| FW | native | brook cinquefoil | Potentilla rivalis | - | - | - | - |
| FU | introduced | bull thistle | Cirsium vulgare | - | - | - | - |
| - | introduced | burr chervil | Anthriscus scandicina | - | - | - | - |
| - | unknown | buttercup | Ranunculus sp. | - | - | - | - |
| FU | native | Canada goldenrod | Solidago canadensis | M | M | M | - |
| FU | introduced | Canadian thistle | Cirsium arvense | M | L | M | - |
| FU | introduced | clasping pepperweed | Lepidium perfoliatum | - | - | - | - |
| F | introduced | climbing nightshade | Solanum dulcamara | - | - | - | - |
| - | native | coastal manroot | Marah oreganus | - | - | - | - |

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| Wetland Status | Native Status | Common Name | Scientific Name | Erosion Control | Short-term revegetation | Long-term revegetation | Wildlife Habitat |
|---|---|---|---|---|---|---|---|
| **Forbes** | | | | | | | |
| F | native | common cowparsnip | Heracleum maximum | M | L | L | - |
| FU | native | common dandelion | Taraxacum officinale | L | L | L | - |
| OW | native | common duckweed | Lemna minor | - | - | - | - |
| - | native | common gaillardia | Gaillardia aristata | - | - | - | - |
| - | introduced | common motherwort | Leonurus cardiaca | - | - | - | - |
| - | introduced | common mullein | Verbascum thapsus | - | - | - | - |
| F | native | common plantain | Plantago major | - | - | - | - |
| - | introduced | common St. Johnswort | Hypericum perforatum | - | - | - | - |
| FU | native | common sunflower | Helianthus annuus | - | - | - | - |
| - | introduced | common tansy | Tanacetum vulgare | - | - | - | - |
| FU | native | common yarrow | Achillea millefolium | - | - | - | - |
| FW | introduced | creeping buttercup | Ranunculus repens | L | H | M | - |
| FU | native | curlycup gumweed | Grindelia squarrosa | - | - | - | - |
| OW | introduced | cutleaf waterparsnip | Berula erecta | - | - | - | - |
| - | native | dock | Rumex sp. | - | - | - | - |
| OW | native | dotted smartweed | Polygonum punctatum | - | - | - | - |
| F | native | feathery false lily of the valley | Maianthemum racemosum | - | - | - | - |
| F | native | Fendler's waterleaf | Hydrophyllum fendleri var. albifrons | - | - | - | - |
| - | native | fernleaf biscuitroot | Lomatium dissectum | - | - | - | - |

**Key:**

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F = faculatative species; occurs in wetlands or uplands
FU = faculatative upland species; occurs in wetlands 1-33% of the time
U = obligate uplands species; always in uplands
- = undetermined

H = high potential
M = medium
L = Low

G = good
F = fair
P = poor

| Wetland Status | Native Status | Common Name | Scientific Name | Erosion Control | Short-term revegetation | Long-term revegetation | Wildlife Habitat |
|---|---|---|---|---|---|---|---|
| **Forbes** | | | | | | | |
| FU | native | fiddleleaf hawksbeard | Crepis runcinata | - | - | - | - |
| FW | introduced | fivehorn smotherweed | Bassia hyssopifolia | - | - | - | - |
| - | introduced | Fuller's teasel | Dipsacus fullonum ssp.sylvestris | - | - | - | - |
| FW | native | giant horsetail | Equisetum telmateia | - | - | - | - |
| F | native | giant sumpweed | Iva xanthifolia | - | - | - | - |
| - | native | Gray's biscuitroot | Lomatium grayi | - | - | - | - |
| - | unknown | groundsmoke | Gayophytum sp. | - | - | - | - |
| - | introduced | gypsyflower | Cynoglossum officinale | - | - | - | - |
| OW | native | hairy pepperwort | Marsilea vestita | - | - | - | - |
| - | native | harlequin blue eyed Mary | Collinsia heterophylla | - | - | - | - |
| - | native | heartleaf arnica | Arnica cordifolia | - | - | - | - |
| - | native | Henderson inflated olsynium | Olsynium douglasii var. inflatum | - | - | - | - |
| - | introduced | hogbite | Chondrilla juncea | - | - | - | - |
| F | native | intermediate dogbane | Apocynum X floribundum | - | - | - | - |
| FW | native | jewelweed | Impatiens capensis | - | - | - | - |
| F | native | lambsquarters | Chenopodium album | - | - | - | - |
| F | native | lambtongue ragwort | Senecio integerrimus | - | - | - | - |

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| Wetland Status | Native Status | Common Name | Scientific Name | Erosion Control | Short-term revegetation | Long-term revegetation | Wildlife Habitat |
|---|---|---|---|---|---|---|---|
| **Forbes** | | | | | | | |
| FW | native | largeleaf avens | Geum macrophyllum | L | L | L | - |
| - | introduced | lesser burrdock | Arctium minus | - | - | - | - |
| - | native | littleflower gilia | Ipomopsis minutiflora | - | - | - | - |
| OW | native | Macoun's buttercup | Ranunculus macounii | - | - | - | - |
| - | introduced | madwort | Asperugo procumbens | - | - | - | - |
| F | native | manyflowered aster | Aster ericoides var. pansus | - | - | - | - |
| OW | native | marsh skullcap | Scutellaria galericulata | - | - | - | - |
| F | native | miner's lettuce | Claytonia perfoliata ssp.perfoliata | - | - | - | - |
| - | native | mint | Mentha sp. | - | - | - | - |
| - | native | Munro's globemallow | Sphaeralcea munroana | - | - | - | - |
| OW | native | narrowleaf cattail | Typha angustifolia | - | - | - | - |
| - | native | needleleaf navarretia | Navarretia intertexta | - | - | - | - |
| F | native | nettleleaf giant hyssop | Agastache urticifolia | - | - | - | - |
| - | native | northern bog violet | Viola nephrophylla var. nephrophylla | - | - | - | - |
| OW | native | northern marsh yellowcress | Rorippa islandica | - | - | - | - |
| - | native | northern willowherb | Epilobium ciliatum ssp. watsonii | - | - | - | - |

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| Wetland Status | Native Status | Common Name | Scientific Name | Erosion Control | Short-term revegetation | Long-term revegetation | Wildlife Habitat |
|---|---|---|---|---|---|---|---|
| **Forbes** | | | | | | | |
| F | native | northwest cinquefoil | Potentilla gracilis | L | M | M | - |
| FW | native | Oregon checkermallow | Sidalcea oregana | - | - | - | - |
| OW | introduced | paleyellow iris | Iris pseudacorus | - | - | - | - |
| FU | native | Pennsylvania pellitory | Parietaria pensylvanica | - | - | - | - |
| F | introduced | perennial pepperweed | Lepidium latifolium | - | - | - | - |
| FW | introduced | poison hemlock | Conium maculatum | - | - | - | - |
| - | native | popcornflower | Plagiobothrys sp. | - | - | - | - |
| F | native | povertyweed | Iva axillaris | - | - | - | - |
| F | introduced | prickly lettuce | Lactuca serriola | - | - | - | - |
| OW | introduced | purple loosestrife | Lythrum salicaria | - | - | - | - |
| F+ | native | purple sweetroot | Osmorhiza purpurea | - | - | - | - |
| - | introduced | redstem stork's bill | Erodium cicutarium | - | - | - | - |
| FW | native | Rocky Mountain iris | Iris missouriensis | - | - | - | - |
| F | native | rough cockleburr | Xanthium strumarium | - | - | - | - |
| OW | native | seaside arrowgrass | Triglochin maritimum | L | L | L | - |
| OW | native | seep monkeyflower | Mimulus guttatus | - | - | - | - |
| F | native | showy milkweed | Asclepias speciosa | - | - | - | - |
| F | introduced | silver cinquefoil | Potentilla argentea | - | - | - | - |
| OW | native | silverweed cinquefoil | Argentina anserina | M | M | M | - |
| - | unknown | smartweed | Polygonum sp. | - | - | - | - |

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U = obligate uplands species; always in uplands
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M = medium
L = Low

G = good
F = fair
P = poor

| Wetland Status | Native Status | Common Name | Scientific Name | Erosion Control | Short-term revegetation | Long-term revegetation | Wildlife Habitat |
|---|---|---|---|---|---|---|---|
| **Forbes** | | | | | | | |
| FW | native | smooth horsetail | Equisetum laevigatum | M | H | M | - |
| - | native | sowthistle | Sonchus sp. | - | - | - | - |
| F | native | starry false Solomon's seal | Maianthemum stellatum | L | L | L | - |
| FU | native | stickywilly | Galium aparine | - | - | - | - |
| FW | native | stinging nettle | Urtica dioica | M | L | L | - |
| OW | native | swamp smartweed | Polygonum hydropiperoides | - | - | - | - |
| F | native | swamp verbena | Verbena hastata | - | - | - | - |
| - | native | sweetcicely | Osmorhiza berteroi | - | - | - | - |
| - | introduced | sweetclover | Melilotus sp. | - | - | - | - |
| FW | native | tall groundwel | Senecio hydrophiloides | - | - | - | - |
| F | native | tall ragwort | Senecio serra | - | - | - | - |
| - | native | tall tumblemustard | Sisymbrium altissimum | - | - | - | - |
| - | native | tansyleaf eveningprimrose | Oenothera tanacetifolia | - | - | - | - |
| - | native | tarweed fiddleneck | Amsinckia lycopsoides | - | - | - | - |
| - | unknown | thistle | Cirsium spp. | - | - | - | - |
| - | native | turpentine wavewing | Pteryxia terebinthina var. terebinthina | - | - | - | - |
| - | native | violet | Viola sp. | - | - | - | - |

**Key:**

| | | |
|---|---|---|
| OW = obligate wetland species; always occurs in wetlands | H = high potential | G = good |
| FW = faculatative wetland species; occurs in wetlands 67-99% of the time | M = medium | F = fair |
| F = faculatative species; occurs in wetlands or uplands | L = Low | P = poor |
| FU = faculatative upland species; occurs in wetlands 1-33% of the time | | |
| U = obligate uplands species; always in uplands | | |
| - = undetermined | | |

| Wetland Status | Native Status | Common Name | Scientific Name | Erosion Control | Short-term revegetation | Long-term revegetation | Wildlife Habitat |
|---|---|---|---|---|---|---|---|
| **Forbes** | | | | | | | |
| OW | native | water knotweed | Polygonum amphibium | M | M | M | - |
| OW | native | water speedwell | Veronica anagallis-aquatica | - | - | - | - |
| OW | introduced | watercress | Rorippa nasturtium-aquaticum | - | - | - | - |
| FW | native | wedgescale saltbush | Atriplex truncata | - | - | - | - |
| FW | native | western goldentop | Euthamia occidentalis | - | - | - | - |
| - | native | western gromwell | Lithospermum ruderale | - | - | - | - |
| - | native | western tansymustard | Descurainia pinnata | - | - | - | - |
| OW | native | western water hemlock | Cicuta douglasii | - | - | - | - |
| FU | introduced | white clover | Trifolium repens | L | M | M | - |
| F | native | whitetip clover | Trifolium variegatum | - | - | - | - |
| - | introduced | whitetop | Cardaria draba | - | - | - | - |
| OW | native | whitewater crowfoot | Ranunculus aquatilis | - | - | - | - |
| F | native | wild mint | Mentha arvensis | - | - | - | - |
| - | native | wild onion | Allium spp. | - | - | - | - |
| FW | native | willow dock | Rumex salicifolius | - | - | - | - |
| - | native | willowherb | Epilobium spp | - | - | - | - |
| - | native | woolly eriophyllum | Eriophyllum lanatum | - | - | - | - |
| - | native | woolly plantain | Plantago patagonica | - | - | - | - |
| FU | introduced | wormseed wallflower | Erysimum cheiranthoides | - | - | - | - |

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| Wetland Status | Native Status | Common Name | Scientific Name | Erosion Control | Short-term revegetation | Long-term revegetation | Wildlife Habitat |
|---|---|---|---|---|---|---|---|
| **Forbes** | | | | | | | |
| - | introduced | yellow salsify | Tragopogon dubius | - | - | - | - |
| - | introduced | yellow sweetclover | Melilotus officinalis | M | H | M | G |

# Appendix B

**National Water Quality Assessment Program: Occurrence of Pesticides in the Yakima and Central Columbia Basins (table adapted from, Ebbert and Embrey 2002; Fuhrer et al 2004; Orme and Kegley 2006 and Williamson et al. 1998).**

[a] H: herbicide, I: insecticide, B: breakdown or degradation product, VOC: Volatile organic compound
[b] all chemicals detected in Yakima were measured from surface water sources
[c] ND: not detected
[d] NM: not measured
-- unknown based on data sources used

| Pesticide | Trade or common name(s) | Type of pesticide[a] | Study Region | | Water Body[b] | | Chemical class |
|---|---|---|---|---|---|---|---|
| Acetochlor | Guardian | H | Yakima River Basin | ND[c] | ND | ND | acetanilide |
| Alachlor | Lasso | H | Yakima River Basin | Central Columbia Plateau | surface-water | ground-water | acetanilide |
| Atrazine | AAtrex | H | Yakima River Basin | Central Columbia Plateau | surface-water | ground-water | triazine |
| Azinphos-methyl | Guthion, Gusathion | I | Yakima River Basin | Central Columbia Plateau | surface-water | ground-water | organophosphorus |
| Benfluralin | Balan, Benefin | H | ND | Central Columbia Plateau | surface-water | ND | dinitroaniline |
| Bentazon | Basagran, bentazone | H | Yakima River Basin | Central Columbia Plateau | surface-water | ground-water | unclassified |
| Bromacil | Hyvar X, Urox B, Bromax | H | NM[d] | Central Columbia Plateau | ND | ground-water | uracil |

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[c] ND: not detected
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| Pesticide | Trade or common name(s) | Type of pesticide[a] | Study Region | | Water Body[b] | | Chemical class |
|---|---|---|---|---|---|---|---|
| Bromoxynil | Buctril, Brominal, Troch | H | NM | Central Columbia Plateau | surface-water | ND | hydroxybenzonitrile |
| Butylate | Sutan +, Genate Plus | H | ND | Central Columbia Plateau | surface-water | ground-water | thiocarbamate |
| Carbaryl | Sevin, Savit | I | Yakima River Basin | Central Columbia Plateau | surface-water | ground-water | carbamate |
| Carbofuran | Furadan, Yaltox | I | ND | Central Columbia Plateau | surface-water | ND | carbamate |
| Chloroethane | Ethyl chloride | VOC | NM | Central Columbia Plateau | -- | ground-water | halogenated organic |
| Chlorpyrifos | Lorsban, Dursban | I | Yakima River Basin | Central Columbia Plateau | surface-water | ground-water | organophosphorus |
| Clopyralid | Stinger, Lontrel, Dowco 290 | H | NM | Central Columbia Plateau | ND | ground-water | pyridinecarboxylic acid |
| Cyanazine | Bladex | H | Yakima River | Central Columbia | surface-water | ground-water | triazine |

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-- unknown based on data sources used

| Pesticide | Trade or common name(s) | Type of pesticide[a] | Study Region | | Water Body[b] | | Chemical class |
|---|---|---|---|---|---|---|---|
| | | | Basin | Plateau | | | |
| DCPA | Dacthal, chlorthal-dimethyl | H | ND | Central Columbia Plateau | surface-water | ground-water | chlorobenzoic acid |
| *p,p'*-DDE | *p,p'*-DDT metabolite | B | Yakima River Basin | Central Columbia Plateau | surface-water | ground-water | DDT degradate |
| Deethylatrazine1 (DEA) | none | B | Yakima River Basin | Central Columbia Plateau | surface-water | ground-water | atrazine degradate |
| Diazinon | Diazinon | I | Yakima River Basin | Central Columbia Plateau | surface-water | ND | organophosphorus |
| Dieldrin | Panoram D-31, Octalox | I | Yakima River Basin | Central Columbia Plateau | surface-water | ground-water | organochlorine |
| 1,2-Dibromoethaned | EDB | VOC | NM | Central Columbia Plateau | -- | ground-water | halogenated organic |
| 1,2-Dichloropropane | Propylene dichloride | VOC | NM | Central Columbia Plateau | -- | ground-water | halogenated organic |

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-- unknown based on data sources used

| Pesticide | Trade or common name(s) | Type of pesticide[a] | Study Region | | Water Body[b] | | Chemical class |
|---|---|---|---|---|---|---|---|
| 1,3-Dichloropropane | Trimethylene dichloride | VOC | NM | Central Columbia Plateau | -- | ground-water | halogenated organic |
| 2,4-D | 2,4-PA | H | Yakima River Basin | Central Columbia Plateau | surface-water | ground-water | chlorophenoxy acid or ester |
| 2,4-DB | Butyrac, embutox | H | NM | Central Columbia Plateau | ND | ground-water | chlorophenoxy acid or ester |
| 2,6-Diethylanaline | none | B | ND | Central Columbia Plateau | surface-water | ground-water | alachlor degradate |
| DCPA | Dacthal, chlorthal-dimethyl | H | ND | Central Columbia Plateau | surface-water | ground-water | alkyl phthalate |
| Dacthal, mono-acid | Dacthal metabolite | H | NM | Central Columbia Plateau | surface-water | ND | polymer |
| Dicamba | Banvel, Mediben, MDBA | H | Yakima River Basin | Central Columbia Plateau | surface-water | ND | benzoic acid |
| Dinoseb | DNBP, Binitro, DN 289 | H | NM | Central Columbia Plateau | surface-water | ground-water | dinitrophenol derivative |

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| Pesticide | Trade or common name(s) | Type of pesticide[a] | Study Region | | Water Body[b] | | Chemical class |
|---|---|---|---|---|---|---|---|
| Diuron | Karmex, Direx, DCMU | H | Yakima River Basin | Central Columbia Plateau | surface-water | ground-water | urea |
| Disulfoton | Di-Syston, Dithiosystox | I | Yakima River Basin | Central Columbia Plateau | surface-water | ND | organophosphorus |
| EPTC | Eptam, Eradicane | H | Yakima River Basin | Central Columbia Plateau | surface-water | ground-water | thiocarbamate |
| Ethalfluralin | Sonalan, Curbit EC | H | Yakima River Basin | Central Columbia Plateau | surface-water | ground-water | dinitroaniline |
| Ethoprophos | Mocap, Prophos | I | Yakima River Basin | Central Columbia Plateau | surface-water | ND | organophosphorus |
| Fonofos | Dyfonate | I | Yakima River Basin | Central Columbia Plateau | surface-water | ND | organophosphorus |
| *alpha*-HCH | *alpha*-BHC, *alpha*-lindane | I | Yakima River Basin | Central Columbia Plateau | surface-water | ND | organochlorine |

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-- unknown based on data sources used

| Pesticide | Trade or common name(s) | Type of pesticide[a] | Study Region | | Water Body[b] | | Chemical class |
|---|---|---|---|---|---|---|---|
| *gamma*-HCH | Lindane, *gamma*-BHC | I | Yakima River Basin | Central Columbia Plateau | surface-water | ND | organochlorine |
| Linuron | Lorox, Linex | H | ND | Central Columbia Plateau | surface-water | ND | urea |
| MCPA | kilsem, metaxon | H | NM | Central Columbia Plateau | surface-water | ND | chlorophenoxy acid or ester |
| Malathion | malathion, maldison, malathon, Cythion | I | Yakima River Basin | Central Columbia Plateau | surface-water | ND | organophosphorus |
| Methyl parathion | Penncap-M | I | ND | Central Columbia Plateau | surface-water | ground-water | organophosphorus |
| Methyl *tert*-butyl ether | MTBE | VOC | NM | Central Columbia Plateau | -- | ground-water | alcohol/ether |
| Metolachlor | Dual, Pennant | H | Yakima River Basin | Central Columbia Plateau | surface-water | ground-water | acetanilide |
| Metribuzin | Lexone, Sencor | H | ND | Central Columbia | surface-water | ground-water | triazine |

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| Pesticide | Trade or common name(s) | Type of pesticide[a] | Study Region | | Water Body[b] | | Chemical class |
|---|---|---|---|---|---|---|---|
| | | | | Plateau | | | |
| Napropamide | Devrinol | H | ND | Central Columbia Plateau | surface-water | ND | amide |
| Norflurazon | Evital, Solicam | H | Yakima River Basin | Central Columbia Plateau | ND | ground-water | pyridazinone |
| Parathion | Thiophos, Bladan, Folidol | I | ND | Central Columbia Plateau | surface-water | ground-water | organophosphorus |
| Pendimethalin | Prowl, Stomp | H | Yakima River Basin | Central Columbia Plateau | surface-water | ground-water | dinitroaniline |
| *cis*-Permethrin | Ambush, Pounce | I | ND | Central Columbia Plateau | surface-water | ND | pyrethroid |
| Prometon | Pramitol | H | Yakima River Basin | Central Columbia Plateau | surface-water | ground-water | triazine |
| Pronamide | Kerb, propyzamid | H | NM | Central Columbia Plateau | surface-water | ND | amide |
| Propyzamide | Kerb | H | ND | **NM** | | | amide |

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[c] ND: not detected
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-- unknown based on data sources used

| Pesticide | Trade or common name(s) | Type of pesticide[a] | Study Region | | Water Body[b] | | Chemical class |
|---|---|---|---|---|---|---|---|
| Propachlor | Ramrod | H | ND | Central Columbia Plateau | surface-water | ND | acetanilide |
| Propanil | Stampede, Surcopur | H | ND | Central Columbia Plateau | surface-water | ND | amide |
| Propargite | Comite, Omite, BPPS | I | Yakima River Basin | Central Columbia Plateau | surface-water | ND | sulfite ester |
| Propham | Chem-Hoe, IPC, prophame | H | NM | Central Columbia Plateau | surface-water | ND | other carbamate |
| Propoxur | Baygon, Blattanex, Unden | I | NM | Central Columbia Plateau | surface-water | ND | N-Methyl Carbamate |
| Simazine | Aquazine, Princep, Weedex | H | Yakima River Basin | Central Columbia Plateau | surface-water | ground-water | triazine |
| 1,1,1-Trichloroethane | Methylchloroform | VOC | NM | Central Columbia Plateau | -- | ground-water | halogenated organic |
| 1,1,2-Trichloro-1,2,2-trifluoroethane | Freon 113, CFC 113 | VOC | NM | Central Columbia Plateau | -- | ground-water | halogenated organic |

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[c] ND: not detected
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-- unknown based on data sources used

| Pesticide | Trade or common name(s) | Type of pesticide[a] | Study Region | | Water Body[b] | | Chemical class |
|---|---|---|---|---|---|---|---|
| 1,2,3-Trichloropropane | Allyl trichloride | VOC | NM | Central Columbia Plateau | -- | ground-water | -- |
| 1,2,4-Trimethylbenzene | Pseudocumene | VOC | NM | Central Columbia Plateau | -- | ground-water | halogenated organic |
| Tebuthiuron | Spike, Perflan | H | Yakima River Basin | Central Columbia Plateau | surface-water | ground-water | urea |
| Terbacil | Sinbar | H | Yakima River Basin | Central Columbia Plateau | surface-water | ground-water | uracil |
| Tetrachloroethene | Perchloroethene | VOC | NM | Central Columbia Plateau | -- | ground-water | -- |
| Tetrachloromethane | Carbon tetrachloride | VOC | NM | Central Columbia Plateau | -- | ground-water | halogenated organic |
| Thiobencarb | Bolero, Saturn, benthiocarb | H | ND | Central Columbia Plateau | surface-water | ND | thiocarbamate |
| Triallate | Far-Go | H | ND | Central Columbia | surface-water | ground-water | thiocarbamate |

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-- unknown based on data sources used

| Pesticide | Trade or common name(s) | Type of pesticide[a] | Study Region | | Water Body[b] | | Chemical class |
|---|---|---|---|---|---|---|---|
| | | | | Plateau | | | |
| Trichloroethene | TCE | VOC | NM | Central Columbia Plateau | -- | ground-water | -- |
| Triclopyr | Garlon, Grazon, Crossbow | H | NM | Central Columbia Plateau | surface-water | ND | chloropyridinyl |
| Trifluralin | Treflan, Trilin | H | Yakima River Basin | Central Columbia Plateau | surface-water | ND | dinitroaniline |
| total Trihalomethanes | -- | VOC | NM | Central Columbia Plateau | -- | ground-water | -- |

# Appendix C

## Agriculture and Associated Pesticides Detected in the Yakima Basin (Table adapted from Ebbert and Embry 2002).

| Pesticide | Percent Detections | Primary Uses |
|---|---|---|
| Acetachlor | 0-54 | Corn silage, corn grain |
| Alachlor | 0-13 | Sweet corn, corn silage, corn grain, peas and beans |
| Atrazine | 94-100 | sweet corn, peas and beans, corn silage, pasture, corn grain |
| Azinphos-methyl | 50-79 | apples, pears, cherries |
| Butylate | 0 | Corn silage, corn grain |
| Carbaryl | 48-100 | apples, asparagus, juice grapes, cherries pears |
| Carbofuran | 0 | alfalfa, sweet corn, corn silage, Wine grapes, other nonorchard, potatoes |
| Chlorpyrifos | 0-21 | apples, corn silage juice grapes, cherries, pears |
| Cyanazine | 0-4.2 | sweet corn, corn silage, corn grain |
| Diazinon | 0-25 | Hops, apples, feedlot, pears, cherries, cattle |
| Disulfoton | 0-17 | asparagus, alfalfa, sweet corn |
| EPTC | 8-21 | alfalfa, sweet corn, corn silage, corn grain |
| Ethalfluralin | 0-4.2 | peas and beans |
| Ethoprophos | 0 | potatoes |
| Fonofos | 0 | sweet corn, corn silage, corn grain, asparagus |
| Lindane | 0 | cattle |
| Linuron | 0 | asparagus |
| Malathion | 0-38 | apples, cherries, alfalfa, feed lot, timothy hay, asparagus |
| Methyl parathion | 0 | apples, sweet corn, corn silage, winter wheat |
| Metolachlor | 0-31 | peas and beans, sweet corn, corn silage, corn grain, sweet silage |
| Metribuzin | 0 | alfalfa, asparagus, potatoes, other nonorchard |
| Pendimethalin | 0-8.3 | peas and beans, mint |
| Phorate | 0 | Corn silage, corn grain, potatoes |
| Propargite | 0-8 | Hops, mint, wine grapes |
| Simazine | 40-83 | apples, pears, wine grapes, juice grapes, asparagus |
| Terbacil | 0-62 | alfalfa, mint |
| Terbufos | 0 | sweet corn, corn grain, corn silage |
| Triallate | 0 | peas and beans |
| Trifluralin | 0-88 | juice grapes, sweet corn, asparagus, peas and beans, potatoes, hops, mint, misc. |

# Appendix D

## Summary of Agro-Riparian Literature Investigating the Efficacy of Buffer Width as a Function of Pollutant Removal.

| Author | Location | Buffer type | Width | Slope | Soil type | Hydrology | Sediments & Nutrients | Pesticides | Summary |
|---|---|---|---|---|---|---|---|---|---|
| Antonious (1999) | Kentucky | No grass; fescue | NA | 10% | silty loam | natural rainfall | NA | Dacthal | Vegetative strips were applied in between crop row to determine if vegetation removed dacthal residues in runoff. **Pesticides:** The fescue removed 95-100% of dacthal from surface water runoff. |
| Daniels and Gilliam (1996) | North Carolina | fescue<br>fescue/riparian forest | 6m<br>20m | -- | sandy loam to clay and silt loam to silt clay | natural rainfall | sediment; nitrogen; phosphorus | NA | **Sediments:** 60-90% reduction. Sediment filtration was positively correlated with distance/width. **Phosphorous:** 60% reduction **Nitrate:** 35-60% reduction |
| Dhondt et al. (2006) | Belgium | grass<br>mixed vegetation<br>forest | 60-70m | <2-15% | NA | groundwater | $NO_3$ | NA | The grass buffer was 97-100% efficient at $NO_3$ removal while the mixed vegetation was 92-100% efficient. The efficiency for the forest buffer ranged 72-90%. |
| Dillaha et al (1989) | Virginia | no buffer<br>orchardgrass<br>orchardgrass | 0<br>4.6m<br>9.1m | 0-4% | silt loam | simulated runoff | sediment; nitrogen; phosphorous | NA | **Sediment:** The first few meters of the VFS were the most effective at trapping sediment. Efficiency of the VFS decreased with time.<br>**Phosphorus:** 49-85% reduction for 4.6m VFS and 65-95% phosphorous reduction for the 9.1m VFS<br>**Nitrogen:** 63% reduction in the 4.6m VFS and a 76% reduction in 9.1m VFS |
| Lee et al. (2000) | Iowa | no buffer<br>switchgrass buffer<br>switchgrass buffer/woody buffer | 0<br>7.1m<br>16.3m | 5-8% | fine-loamy, mixed | simulated runoff | sediment; nitrogen; phosphorus | NA | The grass strips were effective, but the combination of multiple vegetation types and added length of the grass/wood buffer was more effective than the grass buffers.<br>**Sediment:** 7.1m buffer retained 70% of the sediment 16.3m buffer retained >92% of the sediment.<br>**Nutrients:** 7.1m grass buffer removed 44-72% of the nutrients 16.3m grass/woody buffer removed 80-93% of the nutrients. |

| Author | Location | Buffer type | Width | Slope | Soil type | Hydrology | Sediments & Nutrients | Pesticides | Summary |
|---|---|---|---|---|---|---|---|---|---|
| Lee et al. (2003) | Iowa | no buffer<br>switchgrass buffer<br>switchgrass buffer/woody buffer | 0<br>7.1m<br>16.3m | 5-8% | fine-loamy, mixed | natural rainfall | sediment; nitrogen; phosphorus | NA | The buffer removal efficiencies were positively correlated with buffer length.<br>**Sediment:** removal >92% in 7m and > 97% in the 16.3m<br>**Nutrients:** The narrower buffer was effective at sediment and sediment-bound nutrient removal , but the wider buffer increased the removal efficiency of soluble nutrients by 20% |
| Lin et al. (2004) | Missouri: laboratory greenhouse | orchard grass<br>smooth bromegrass<br>tall fescue<br>timothy<br>switchgrass | NA | NA | sandy loam | NA; pesticide was sprayed on plants | nitrate | atrazine and Balance (isoxaflutole) | Switchgrass, tall fescue, and smooth bromegrass yielded the most promising results for soil remediation of atrazine, Balance, and nitrate |
| Lowrance et al (2005) | Georgia | grass strip;<br>managed forest<br>unmanaged forest | 8m<br>45-60m<br>15m | 2.50% | loamy sand | Natural surface runoff | Nitrogen and Phosphorous | NA | **Nutrients:** the highest reduction of nutrients occurred in the grassed buffer strip |
| Mander et al. (1997) | Estonia | 14-year-old grey alder stand<br>40-year-old grey alder stand | 20m<br>28m | -- | -- | -- | nitrogen | NA | **Nutrients:** higher removal rates are achieved by buffers composed of multiple species and vegetative types also, shrubs and young trees are more effective. |
| Mickelson et al (2003) | Iowa | VFS<br>VFS | 4.6m<br>9.1m | 3-6% | fine-loamy | simulated rainfall | sediment | atrazine | **Sediment:** 4.6m strip reduced sediment by 70.5% and the 9.1m strip reduced sediment by 87.2%<br>**Atrazine:** The width of the filter strip was positively correlated to herbicide reductions. The 4.6m strip reduced atrazine by 31.2% and the 9.1m strip reduced atrazine by 79.1%. |

| Author | Location | Buffer type | Width | Slope | Soil type | Hydrology | Sediments & Nutrients | Pesticides | Summary |
|---|---|---|---|---|---|---|---|---|---|
| Oelbermann and Gordon (2000) | Ontario | Forest buffer<br>thinned forest buffer<br>forest buffer | 50-100m<br>10-50m<br>2-5m | -- | loam | NA | litterfall | NA | **Litterfall**: litterfall was significantly higher in stream reach with the widest buffer |
| Osborne and Kovacic (1993) | Illinois | row crops<br>riparian forest<br>reed canary grass buffer | 0<br>16m<br>39m | -- | silty clay loam | groundwater | Nitrogen and Phosphorous | NA | **Nitrate:** forested buffers were more effective at nitrate reductions<br>**Phosphorous:** the grass buffer strip was more effective at P retention than the forested buffer |
| Patty et al. (1997) | France | mixed grasses<br>mixed grasses<br>mixed grasses<br>mixed grasses | 0<br>6m<br>12m<br>18m | -- | silt loam | Natural rainfall. | NA | lindane; atrazine; isoproturon; diflufenican | **Pesticides:** removal effectiveness ranged 76-100% for all pesticides tested at all buffer widths. The wider widths were more effective at pollutant removal. |
| Pearce et al. (1997) | Wyoming; laboratory | Kentucky bluegrass<br>Kentucky bluegrass<br>Kentucky bluegrass | 12.5cm<br>25cm<br>50cm | 9% | sandy loam | simulated rainfall | sediment | NA | **Sediment:** larger widths were more effective at sediment removal |
| Peterjohn and Correll (1984) | Maryland | 50m of riparian forest | 50m | basin: 5% | fine sandy loam | groundwater and surface runoff | Nitrogen and Phosphorous | NA | **Nitrate:** forested buffers retained 89% of nitrogen<br>**Phosphorous:** forested buffer retained 80% of phosphorous |
| Rankins et al. (2001) | Mississippi | no buffer<br>big bluestem<br>eastern gamagrass<br>switchgrass<br>tall fescue | 30cm | 3% | silt clay | natural and simulated rainfall | sediment | fluometuron; norflurazon | **Sediment:** each of the grasses reduced sediments by at least 66%.<br>**Herbicide:** reductions by all four grasses were ≥59% for fluometuron. Norflurazon was reduced by at least 46% for each of the grasses. |
| Robinson et al. (1996) | Iowa | Bromegrass | 18.3m | 7%<br>12% | silty-loam | Natural rainfall. | sediment | NA | **Sediment:** 12% gradients experienced greater sediment loss than the 7% slopes. The VFS removed 85% of the sediment at 9.1m on both slope conditions. Beyond 9.1m sediment loss was negligible. |

| Author | Location | Buffer type | Width | Slope | Soil type | Hydrology | Sediments & Nutrients | Pesticides | Summary |
|---|---|---|---|---|---|---|---|---|---|
| Schmitt et al. (1999) | Nebraska | grain sorghum<br>grasses<br>grasses-trees combined | 0<br>7.5m<br>15m | 6-7% | silty clay loam | simulated runoff | sediment; nitrogen; phosphorus | atrazine; alachlor; permethrin; bromide | **Sediment:** for all buffer types; 7.5m widths were 77% effective at sediment removal while 15m widths were 85% effective.<br>**Nutrients:** phosphorus was more effectively reduced by the buffer than nitrogen due to the high sorption of total phosphorous with sediment particles.<br>**Pesticides:** Atrazine and alachlor had the lowest reductions due to high solubility of these chemicals.<br>**Width vs. vegetation type:** The underlying results of this study indicate buffer width is positively correlated to the efficiency of contaminant removal. |
| Schultz et al. (1995) | Iowa | switchgrass<br>shrubs<br>trees | 7m<br>3.2m<br>8-10m | "gentle" | NA | groundwater | Nitrogen | atrazine | **Nitrate and Atrazine:** the multi-species riparian buffer zone is effective at reducing these forms of pollution at each of the three zones. |
| Smith et al. (2006) | North Carolina | mixed vegetation: grasses, shrubs, and trees | 9m<br>30m | -- | coarse-loamy | groundwater | nitrate | NA | **Nitrate:** reductions in the 9m buffer ranged 35-53%. Reductions of nitrate in shallow groundwater ranged 95-93% in the 30m buffer. |
| Sovell et al. (2000) | Minnesota | grass buffer<br>wooded buffer<br>rotationally grazed buffer | -- | -- | -- | surface water (stream) | sediment and turbidity | NA | **Turbidity:** sites with grass buffers yielded lower turbidity than wooded buffers.<br>**Sediment:** grass buffers had a lower percentage of fine sediments than wooded buffers. Grass buffers had a lower percentage of fine sediments than wooded buffers.<br>**Canopy cover:** both grassed buffers and wooded buffers yielded comparable canopy cover results. |
| Staddon et al. (2001) | Mississippi | no buffer<br>mixed grasses | NA | NA | silt loam | NA | NA | metolachlor | **Soil Attributes:** compared with the bare plot soils, the VFS plots yielded significantly higher organic carbon and elevated sorption capacity for metolachlor. Metolachlor was broken down more readily in the VFS than the bare plots. |

| Author | Location | Buffer type | Width | Slope | Soil type | Hydrology | Sediments & Nutrients | Pesticides | Summary |
|---|---|---|---|---|---|---|---|---|---|
| Syversen & Bechmann (2004) | Norway | mixed grasses | 5m | 14% | silty clay loam | simulated runoff | sediment | glyphosate; propiconazole; fenpropimorph | **Sediment:** Average removal efficiencies were 62%. **Pesticides:** removal efficiencies are as follows; glyphosate: 39%; propiconazole: 63%; and fenpropimorph: 71%. |
| Young and Briggs (2005) | New York | mixed grasses<br>salix-grass<br>forested riparian buffer | 9m<br>9m<br>10m | 0-6% | silt loam | groundwater | nitrogen | NA | **Nitrogen:** soil type strongly influenced $NO_3$-N concentrations. Forest buffers yielded the lowest $NO_3$-N concentration |